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NAFEC RANGE INSTRUMENTATION SYSTEMS,(U)

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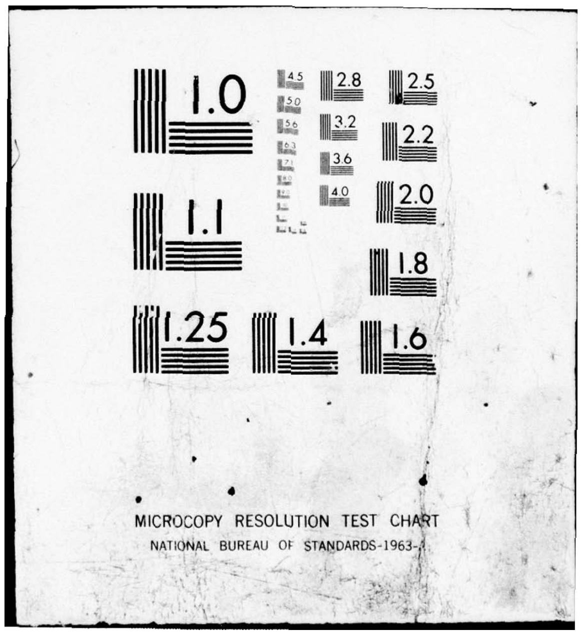
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Report No. FAA-NA-79-32

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NAFEC RANGE INSTRUMENTATION SYSTEMS

V.J. LUCIANI

DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

FEBRUARY 1980

NAFEC REPORT

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FEDERAL AVIATION ADMINISTRATION
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16. Abstract

This report documents the inventory of National Aviation Facilities Experimental Center (NAFEC) range instrumentation systems used to provide reference position measurements and recording in support of NAFEC and other-user projects. Each system is described briefly to include system specifications, a summary of estimated errors, sample data listings, and how the data are processed.

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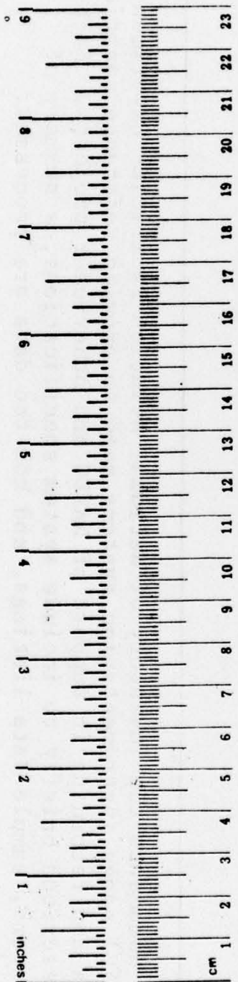
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

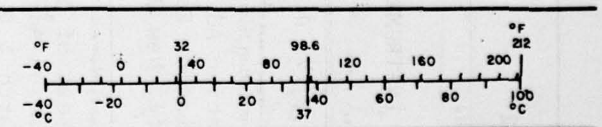
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

This document provides potential users of the NAFEC range instrumentation facilities with information on the functions, capabilities, and applications of these facilities.

LIST OF FACILITIES.

NAFEC's range instrumentation complex includes the following facilities:

1. A three-station phototheodolite system; an optical instrumentation complex that measures and records aircraft azimuth/elevation data for conversion into aircraft space position.

2. A laser tracking system; a mobile facility that uses a laser beam to measure and record aircraft slant range, azimuth, and elevation angles for conversion into aircraft space position.

3. An Extended Area Instrumentation Radar (EAIR); a C-band instrumentation radar system that measures and records aircraft position in slant range, azimuth, and elevation angles.

4. A Nike/Hercules modified radar system; includes two X-band missile and target tracking radars converted into instrumentation radars to provide aircraft position measurement and recording from each radar of slant range, azimuth, and elevation angles.

5. An air-to-air ranging and bearing system; utilizes digitized Tactical Air Navigation Aid (TACAN) sets to provide measurement and recording of slant range between two aircraft, and the relative bearing to aircraft when equipped with a TACAN rotating antenna.

6. Range Control; provides communications, control, and coordination of National Aviation Facilities Experimental Center (NAFEC) flight tests that use any of the range instrumentation facilities; central point for receiving and processing data from each phototheodolite site; provides central timing to all facilities and users.

Physical locations of these facilities are shown on the NAFEC range map, (figure 1).

RANGE CAPABILITY.

Each of the above range facilities has specific coverage characteristics that are pertinent to the type of flight test program it supports. For example, flight test programs that are related to landing systems in which test data are acquired on approaches would use the phototheodolite system for reference data. The phototheodolite system coverage is dependent upon visibility

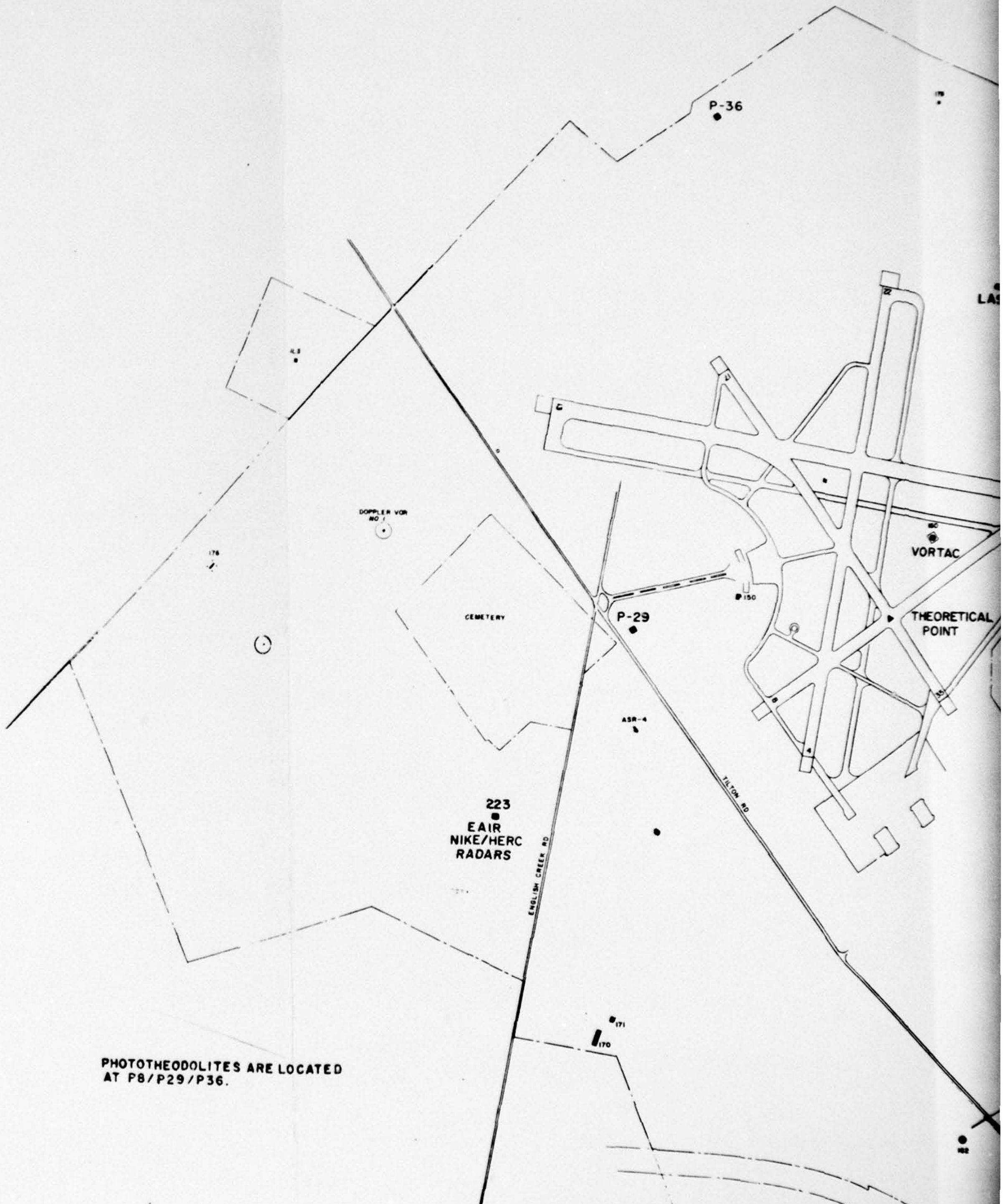
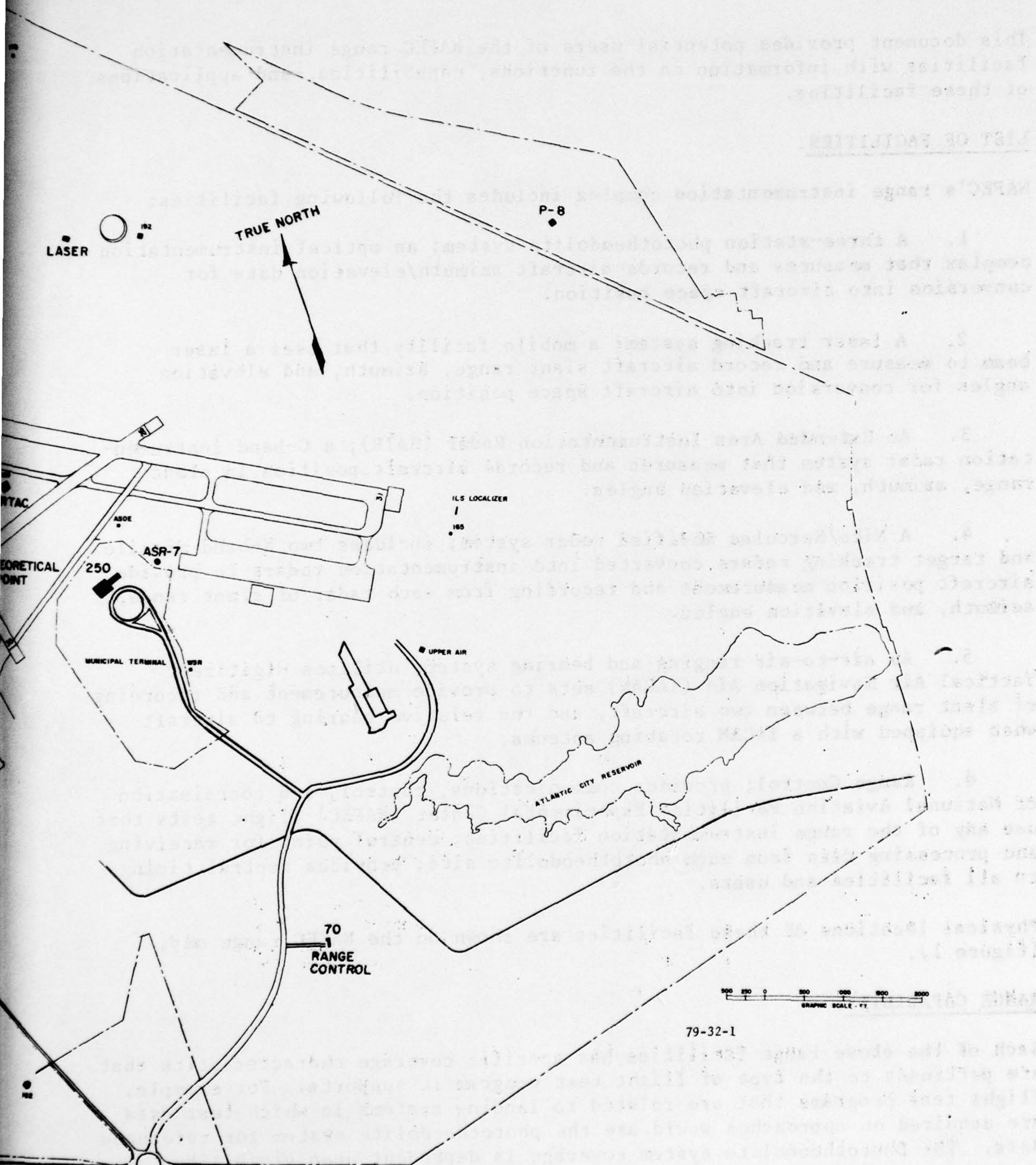


FIGURE 1. NAFE



NAFEC RANGE MAP

conditions to provide aircraft tracking from touchdown to a maximum of 10 to 15 nmi.

For similar flight test programs where data further from touchdown are required, the laser can be used. Laser coverage typically extends from touchdown to a maximum distance of 25 nmi, again subject to weather conditions because the laser principle is one of transmitting and reflecting a light beam.

In navigation system projects where data may be required at locations 25 nmi or more from NAFEC, the EAIR or Nike/Hercules radars are used. Depending upon aircraft altitude, coverage from these radars can be obtained out to a maximum distance of 200 nmi.

Although multitarget tracking is available with the three radars, the air-air ranging system is an onboard device that provides slant range between two or more aircraft. This system is particularly useful as reference for project tests such as collision avoidance flights where separation distance is of prime concern.

GRID COORDINATES.

NAFEC makes use of a special grid system for the phototheodolite system. Its theoretical origin is a point located on the airfield as shown in figure 1. The axes of the NAFEC grid are aligned parallel to runway 13-31, the main NAFEC runway.

In contrast, the EAIR and Nike/Hercules radars are True North oriented in geodetic coordinates. The displacement from NAFEC zero (+Y) to True North is 62.01297°.

Coordinate conversion, translation of origin and rotation of axes, can be performed real-time for display of aircraft trajectory/position. For postflight processing and analysis, data are recorded at each facility for processing through the NAFEC central computer complex, a Honeywell Model 66/60 computer. Merge of independent project data and instrumentation facility data is also handled on the 66/60 computer.

NAFEC COMPUTER.

Instrumentation data tapes are processed on NAFEC's Honeywell Level 66 Series 60 computer (figure 2), which offers: local and remote job entry in which any program that can be entered locally can also be entered from a remote input/output terminal; time sharing to give users at remote locations full batch-processing service and time-sharing capabilities; direct program access to provide terminal access to a program in execution; and interactive remote job entry to let remote users create a batch program, to enter or debug it, to inspect its output, and to converse with it.

Hardware inventory on the 66/60 includes: 15 tape drives, of which 12 are 9-track and three are 7-track; card punch, card reader, and two 1,200-lines-

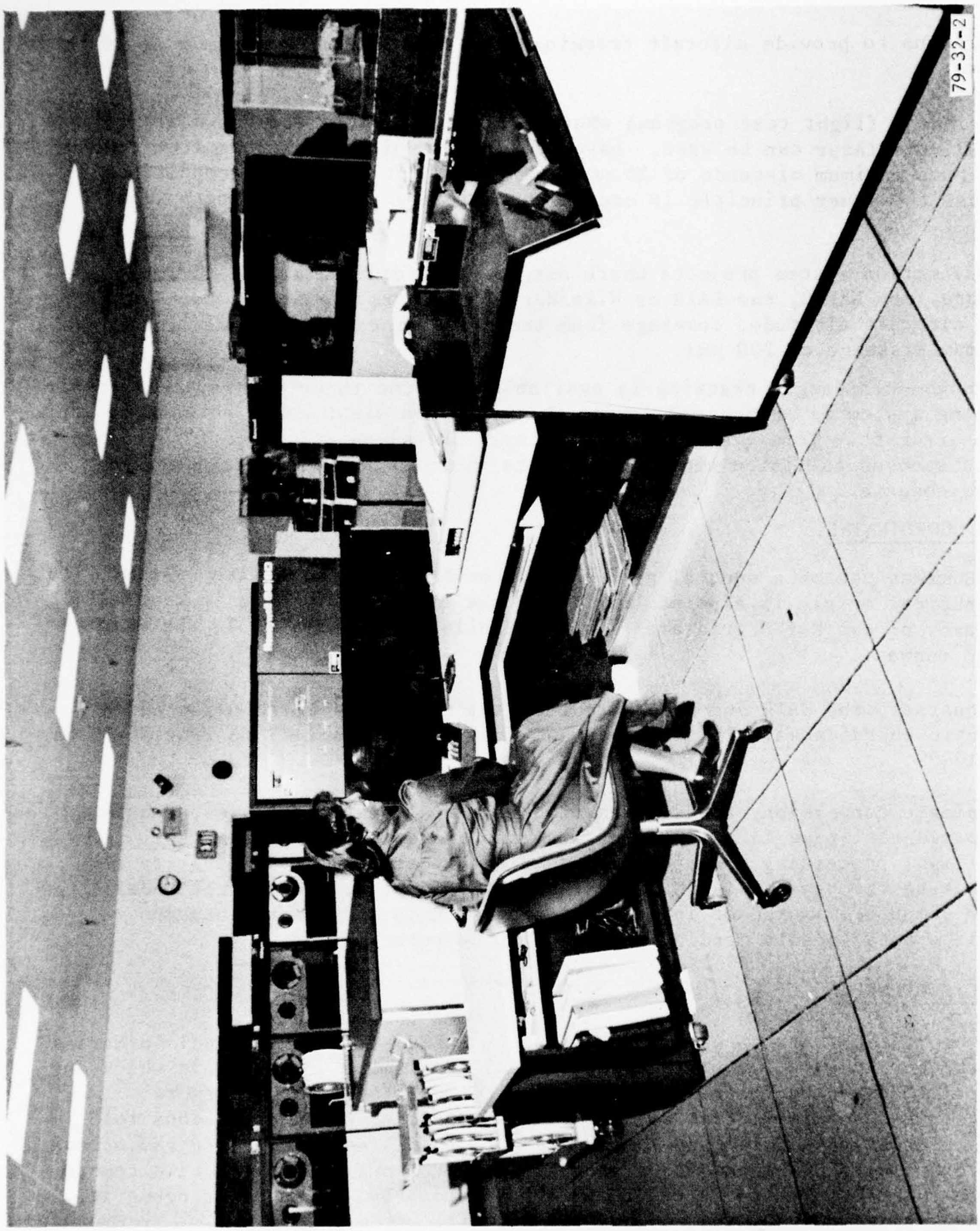


FIGURE 2. NAFEC CENTRAL COMPUTER

per-minute (lpm) printers; 8 disk drives (mass storage); and 72 remote terminals including "smart" terminals which have graphic cathode ray tube (CRT) display, dual processors, and memory to function either interactively with the 66/60 or independently as a functional minicomputer. Graphic display terminals permit online design, modification, enhancement, or debugging of data plots, with light pens or cursors available to operate on specific data points. A Cal Comp pen-plotting system is used to make graphical displays of data.

Total memory for the 66/60 computer is 256k, 36-bit words, of which 128k are in central memory, and 128k in the control unit.

CENTRAL TIMING SYSTEM.

NAFEC's central time system (figure 3) is located at Range Control Center, from which a master time code is distributed real-time in the form of time-of-day code pulses and control pulses to all range instrumentation facilities and to any other facilities, including aircraft, requiring time correlation of data.

Real-time code pulses are distributed via landlines, VHF radio link, and leased telephone lines to locations external to NAFEC. Distribution of the time code is accomplished at the Supervisor's Console in Range Control Center.

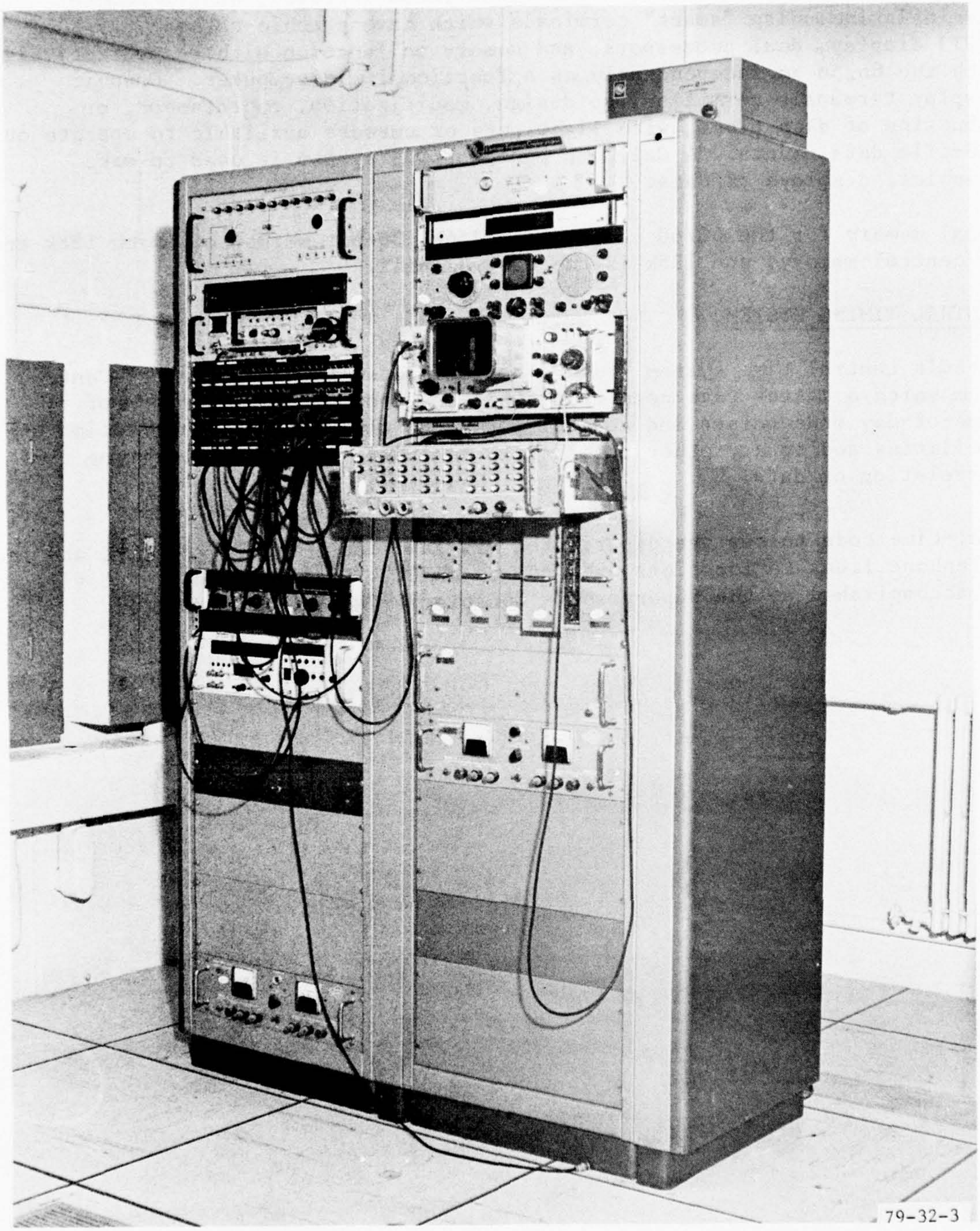


FIGURE 3. CENTRAL TIMING SYSTEM

PHOTOTHEODOLITE SYSTEM

NAFEC's phototheodolite complex consists of a three-station photo-optical instrumentation complex that is used to accurately determine reference position in the airport area. Data outputs of each phototheodolite station are transmitted to the Range Control Facility where they are processed, displayed, and recorded.

Each of the phototheodolite stations is located on a specially constructed tower platform. A typical station is shown in figure 4. Figure 5 is a view of the phototheodolite instrument, a Contraves Model C.

During tracking, two operators man each instrument, one to control the azimuth drive and the other to control the elevation drive. The dome is slaved to the azimuth drive so that it rotates with the instrument.

Each phototheodolite measures azimuth and elevation angles to the target under track. Angle encoders digitize data that are transmitted to Range Control via landline.

REAL-TIME PROCESSOR.

At Range Control a real-time display and recording system, shown in figure 6, accepts the angular and time data at its inherent rate of 20 times per second and performs the following functions.

1. A computer-format recorder records the raw data in format suitable for processing on the Honeywell 66/60 computer.

2. A coordinate conversion program accepts the angular/time data from any selected pair of phototheodolites and converts the angular data into rectangular coordinates of XYZ and time.

3. Outputs of the coordinate conversion program are applied to a plotting board via a digital-analog converter which supplies the voltages that drive the plotter arms. Two pens are available to permit plotting any of two trajectories, XY, XZ, or YZ, simultaneously.

4. Raw data are also recorded on a separate tape for use as a backup record in case the online tape is damaged during further processing.

DATA FLOW.

Typical processing of phototheodolite data in support of NAFEC projects is shown on the data flow chart of figure 7. The following description is numerically keyed to this diagram.

NAFEC phototheodolite stations (1) are identified by number as P8, P29, and P36.

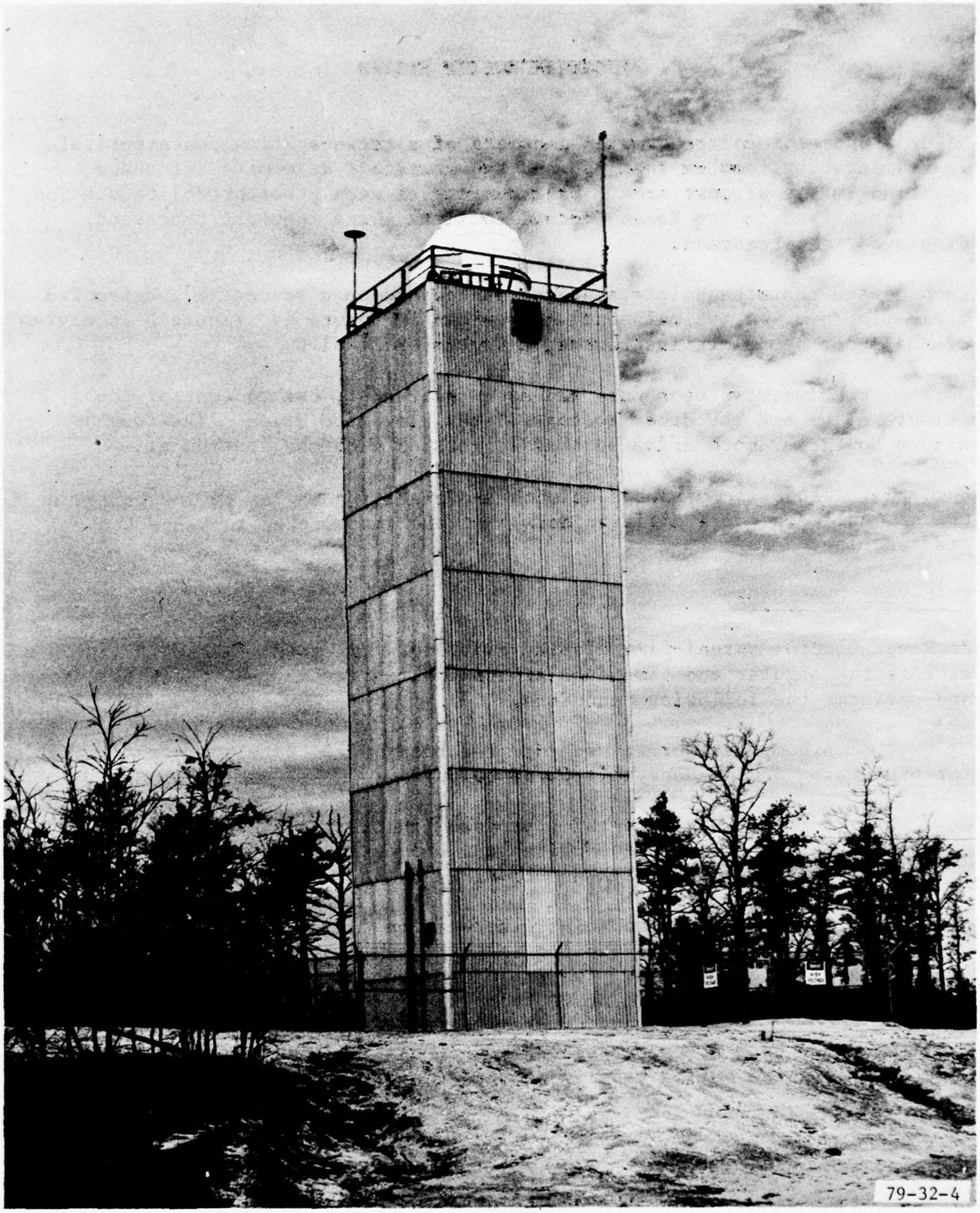


FIGURE 4. PHOTOTHEODOLITE TOWER

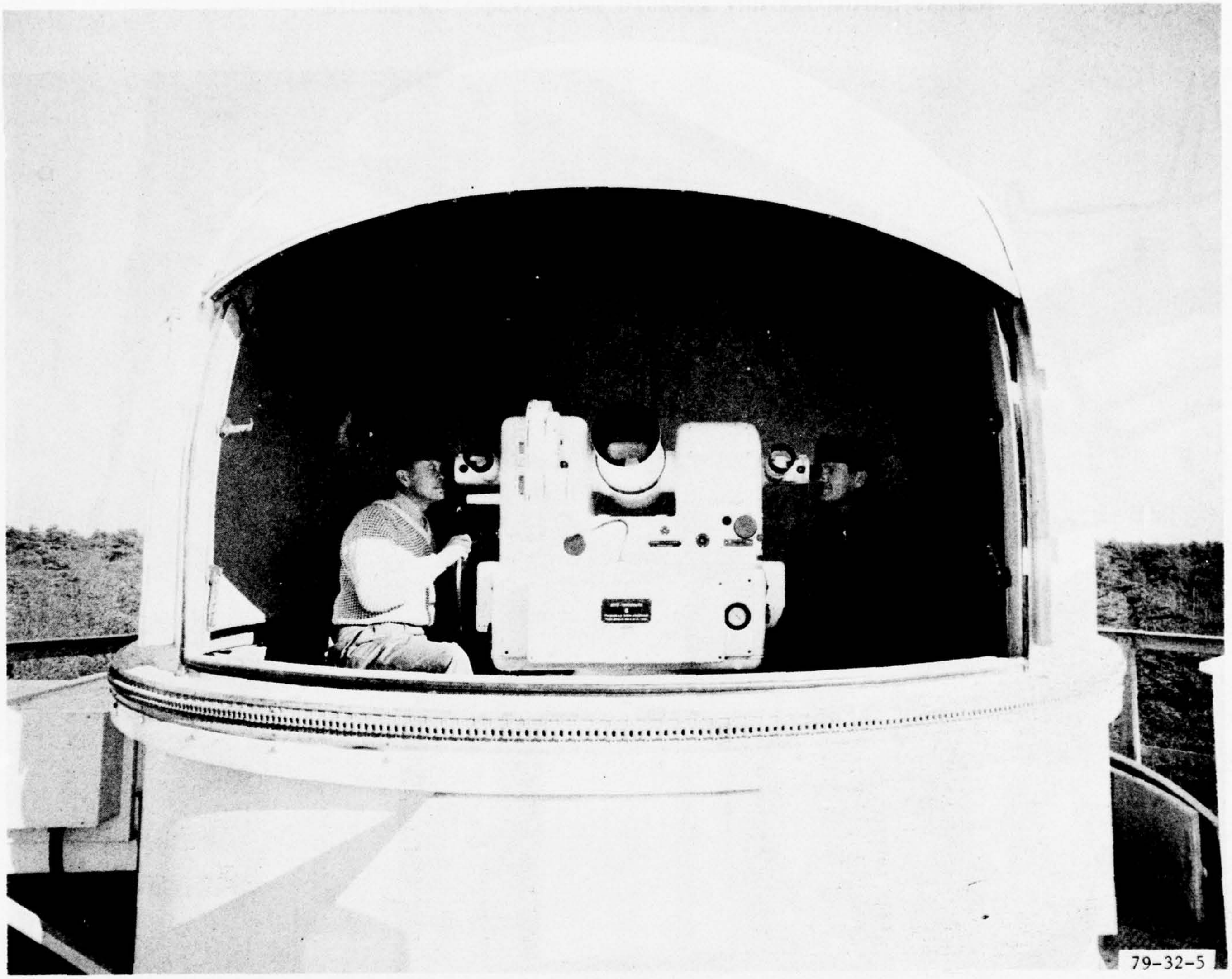


FIGURE 5. PHOTOTHEODOLITE INSTRUMENT

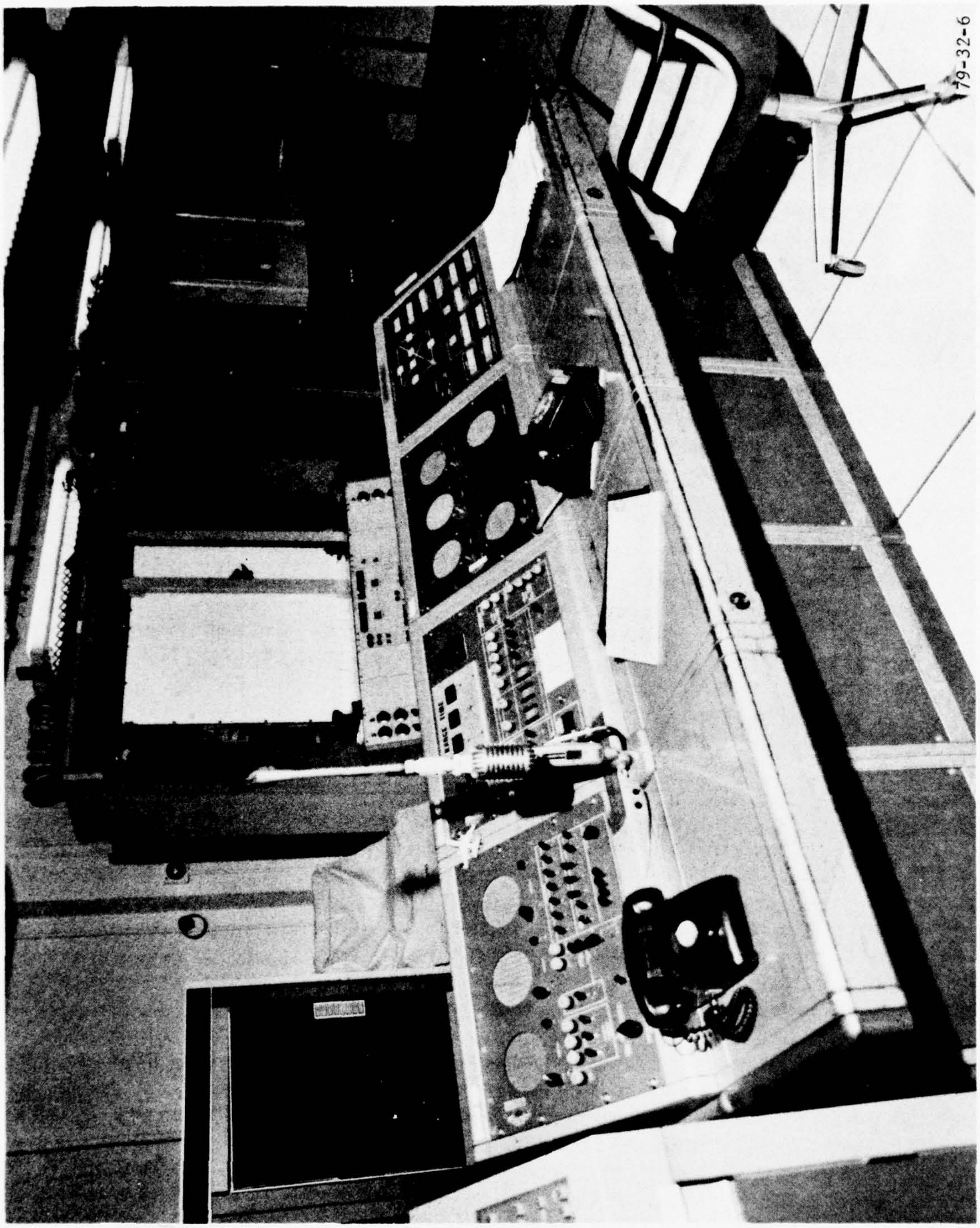


FIGURE 6. REAL-TIME DISPLAY AND RECORDING SYSTEM

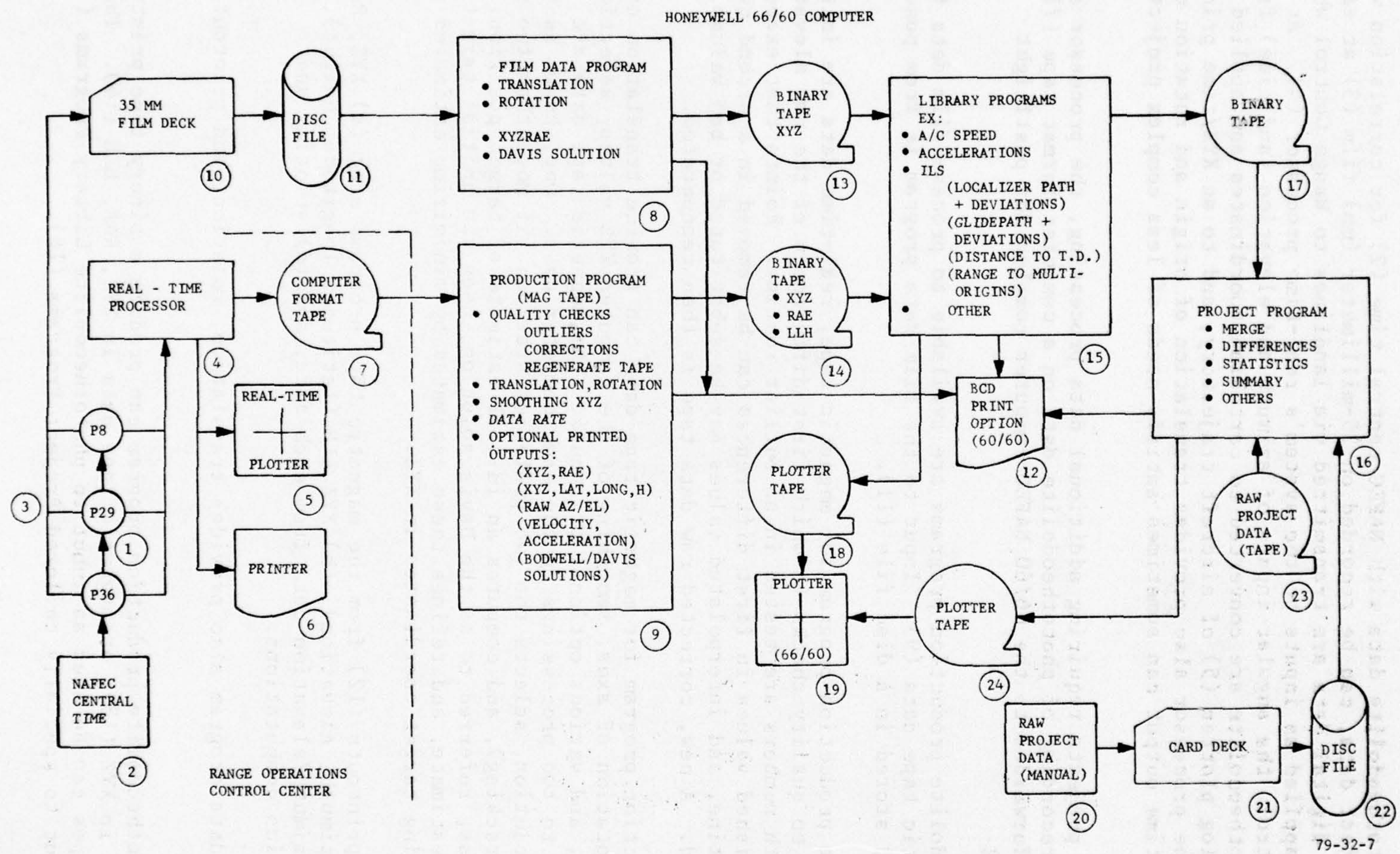


FIGURE 7. PHOTOTHEODOLITE DATA FLOW

Basic phototheodolite data with NAFEC central time (2) for correlation with other project data, can be recorded on 35-millimeter (mm) film (3) at each site, and digital data are transmitted via landlines to Range Control where they are applied as inputs to the system's real-time processor (4). At Range Control, the angular inputs of azimuth and elevation (and time) from each phototheodolite are converted to cartesian coordinates and applied to an XY/XZ analog plotter (5) of aircraft trajectory, and to an XYZ/time printer (6). Because the processor also provides translation of origin and rotation of axes, the real-time output can sometimes satisfy needs of less complex projects directly.

For those projects requiring additional data processing, the processor also provides recording of phototheodolite data on a computer format tape (7) which is forwarded to the 66/60 NAFEC computer complex for postflight processing.

Phototheodolite production programs are available to process film data (8) and magnetic tape data (9). Input to the film data program is from punched cards (10) stored in a disc file (11).

Within the production program for magnetic tape, real-time data are initially subjected to quality checks in which first differences of the raw elevation and azimuth numbers are tested in an outlier routine. Points that exceed preestablished values in first differences can be removed in a second quality check routine, and interpolated values may be substituted or bad values can be deleted. A new, corrected raw data tape is then regenerated.

The production program for magnetic tape data can provide translation of origin, rotation of axes, smoothing of the computed XYZ values, selection of data rate, and various optional printouts. The magnetic tape data are subjected to two processings on the same computer pass. One, known as the Bodwell solution, selects the two preferred stations (if more than two were used in tracking), and computes an initial estimate of target position. The second pass, referred to as the Davis solution, uses the initial target position estimate, and refines these estimates by minimizing estimated errors in computing target coordinates in XYZ.

Optional printouts (12) from the magnetic tape programs are; (a) XYZ, RAE (range, azimuth, elevation), (b) XYZ LLH (latitude, longitude, height), (c) raw azimuth/elevation data from each site, and (d) velocity and acceleration computations.

The film data program also provides translation, rotation, and printout of XYZ, RAE.

Each phototheodolite production program can produce a binary tape printout of film data in XYZ (13), or magnetic tape data in XYZ, RAE, LLH (14). These binary tapes can be used as input to phototheodolite Library Programs (15), or as input to specially tailored Project Programs (16).

The Library Program can provide an output binary tape (17) as input to the Project Program, a plotter tape (18), which is plotted on the 66/60 digital plotter (19) or optional printouts. Printouts at this level frequently satisfy project needs.

Other inputs to the Project Program are typically various project data collected manually (20) and reduced to cards (21) for storage on a disc file (22), or project data collected on magnetic tape (23). This program merges phototheodolite data with project data to provide comparative differences of key parameters such as angular differences in, for example, a localizer, glidepath, or VOR bearing. These differences are then generally operated on to produce a statistical summary of project system errors which, along with plots, are the final output upon which project reports are based.

A sample phototheodolite film record is shown in figure 8 and a sample of XYZ, RAE output data in figure 9.

SYSTEM ACCURACY.

The accuracy with which phototheodolites can measure and derive space position data is a function of target location with respect to the baseline of the two stations used to compute a given point. Constant factors that enter into the computation of position error include the baseline length, and the value of maximum angular error which depends on whether magnetic tape data or film records are processed.

The basic phototheodolite distance error equation is from report RE-173, "Precision of Line-of-Sight Intersection Using Two Theodolites," by J. W. Fecker, Inc., dated March 2, 1959.

The error equation is:

$$E = (B)(e)(d)$$

where:

E = maximum potential distance error, in feet,
B = baseline distance, in feet,
e = maximum estimated angular error, in radians,
d = location error factor, dimensionless.

Values of B for the NAFEC phototheodolites are:

B_1 (P29/P36) = 6,468 feet
B_2 (P36/P8) = 10,084 feet
B_3 (P29/P8) = 11,816 feet.

Values of e, established from controlled measurements are:

$e_1 = 4.83 \times 10^{-5}$ radians based on rigid quality control of film records,
$e_2 = 9.66 \times 10^{-5}$ radians based on standard film reading procedures,
$e_3 = 43.49 \times 10^{-5}$ radians based on using magnetic tape data.

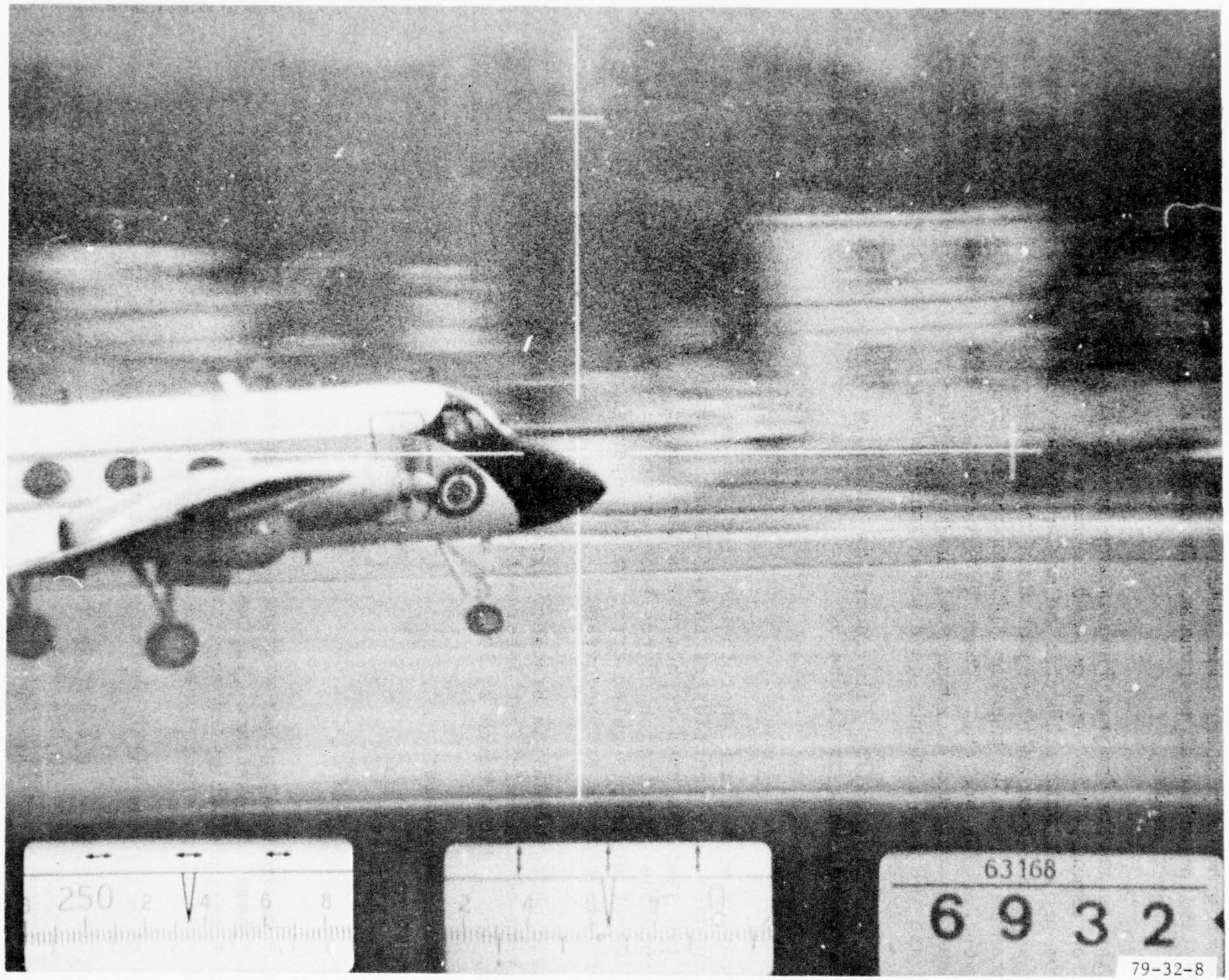


FIGURE 8. PHOTOGRAPHIC FILM SAMPLE

F A A / N A F E C   PHOTOTHEODOLITE   DATA   USING   NAFEC   CARTESIAN   AND   SPHERICAL   COORDINATE   SYSTEMS   PAGE NO. 21

NOISE TEST 930 C03 145   R 327 F 079 P8 29 36

SITES USED   P29   P36   P8   DATE 6 14 78   RUN NO. 17

TIME HRS	MIN	SEC	X (FT.)	Y (FT.)	Z (FT.)	SLANT RANGE (FT.)	AZIMUTH ANGLE DEGREES	ELEVATION ANGLE DEGREES
9	21	54.00	6838.3	-42.7	1222.4	6946.8	90.4	10.1
9	21	54.10	6850.0	-41.9	1225.8	6958.9	90.4	10.1
9	21	54.20	6861.4	-41.7	1229.9	6970.8	90.3	10.2
9	21	54.30	6873.2	-41.8	1233.7	6983.1	90.3	10.2
9	21	54.40	6885.6	-41.4	1237.2	6996.0	90.3	10.2
9	21	54.50	6896.8	-40.8	1240.5	7007.6	90.3	10.2
9	21	54.60	6908.4	-41.3	1244.1	7019.6	90.3	10.2
9	21	54.70	6919.4	-40.7	1248.5	7031.3	90.3	10.2
9	21	54.80	6931.8	-41.0	1251.6	7044.0	90.3	10.2
9	21	54.90	6942.9	-40.3	1254.3	7055.4	90.3	10.2
9	21	55.00	6954.7	-39.8	1257.6	7067.6	90.3	10.2
9	21	55.10	6965.6	-39.6	1260.3	7078.9	90.3	10.3
9	21	55.20	6977.3	-39.2	1264.4	7091.1	90.3	10.3
9	21	55.30	6988.9	-38.6	1268.4	7103.1	90.3	10.3
9	21	55.40	7000.4	-39.1	1271.5	7115.0	90.3	10.3
9	21	55.50	7011.9	-39.6	1275.4	7127.0	90.3	10.3
9	21	55.60	7023.6	-39.3	1278.6	7139.1	90.3	10.3
9	21	55.70	7035.2	-38.9	1282.6	7151.3	90.3	10.3
9	21	55.80	7047.3	-39.3	1285.1	7163.6	90.3	10.3
9	21	55.90	7057.6	-38.4	1289.6	7174.6	90.3	10.4
9	21	56.00	7069.2	-38.5	1293.0	7186.6	90.3	10.4
9	21	56.10	7081.7	-38.5	1295.9	7199.4	90.3	10.4
9	21	56.20	7093.9	-37.8	1299.2	7212.0	90.3	10.4
9	21	56.30	7105.5	-37.9	1302.6	7224.0	90.3	10.4
9	21	56.40	7117.2	-36.2	1305.8	7236.1	90.3	10.4
9	21	56.50	7129.8	-37.4	1309.4	7249.1	90.3	10.4
9	21	56.60	7140.6	-36.2	1313.1	7260.5	90.3	10.4
9	21	56.70	7152.5	-36.5	1316.6	7272.7	90.3	10.4
9	21	56.80	7164.1	-36.3	1320.1	7284.8	90.3	10.4
9	21	56.90	7175.7	-37.2	1323.5	7296.8	90.3	10.4
9	21	57.00	7187.5	-36.5	1326.6	7308.9	90.3	10.5
9	21	57.10	7199.1	-36.4	1330.0	7321.0	90.3	10.5
9	21	57.20	7211.0	-35.8	1333.6	7333.4	90.3	10.5
9	21	57.30	7223.3	-36.1	1336.4	7346.0	90.3	10.5
9	21	57.40	7235.0	-35.4	1340.2	7358.2	90.3	10.5
9	21	57.50	7247.1	-35.3	1343.2	7370.6	90.3	10.5
9	21	57.60	7258.8	-34.7	1347.0	7382.8	90.3	10.5
9	21	57.70	7270.3	-34.0	1350.8	7394.8	90.3	10.5
9	21	57.80	7281.1	-33.0	1354.4	7406.0	90.3	10.5
9	21	57.90	7292.3	-33.0	1357.3	7417.6	90.3	10.5
9	21	58.00	7303.5	-31.9	1360.7	7429.2	90.3	10.6
9	21	58.10	7316.2	-31.8	1363.9	7442.3	90.2	10.6
9	21	58.20	7327.1	-31.4	1367.4	7453.7	90.2	10.6
9	21	58.30	7339.8	-31.1	1370.3	7466.7	90.2	10.6
9	21	58.40	7352.0	-31.6	1373.0	7479.1	90.2	10.6
9	21	58.50	7362.8	-31.1	1376.7	7490.4	90.2	10.6
9	21	58.60	7374.4	-30.8	1380.1	7502.5	90.2	10.6
9	21	58.70	7386.0	-30.4	1383.4	7514.5	90.2	10.6
9	21	58.80	7398.6	-30.8	1385.9	7527.4	90.2	10.6
9	21	58.90	7409.5	-30.2	1389.1	7538.7	90.2	10.6

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FIGURE 9. SAMPLE PHOTOTHEODOLITE DATA LISTING

Since terms B and e are constant for any given measurements, they are more readily applied as a constant, as given in the following table:

TABLE 1. $K = B_i e_j$.

	B_1 (29/36)	B_2 (8/36)	B_3 (8/29)
e_1 (Film-qual.)	0.31	0.49	0.57
e_2 (Film-std.)	0.62	0.97	1.14
e_3 (Real-time)	2.81	4.38	5.14

The error equation then simplifies to:

$$E = Kd.$$

Quick application of this equation can be done using either of the charts (figures 10 or 11) on which curves of d are plotted for given target X, Y coordinates in terms of baseline distances. Figure 11 is an expanded version of figure 10, and is used to compute errors for points close in.

To use these charts, assume, for example;

(1) use of phototheodolite pair P8 and P36,
(2) use of magnetic tape data,
(3) target at point P, figure 10.

Although, in this example, target location is specified on the chart, it is normally necessary to establish target X, Y coordinates normalized to the selected baseline. For example, P8/P36 baseline has a length of 10,084 feet, therefore the target, P, which is four baselines distant in X and Y, would have coordinates, X = 40,336 feet, Y = 40,336 feet.

Having established the location of the target on the chart, simply read its d-value; in this case, d = 90.

$E = Kd = (4.38)(90) = 394$ feet, for a target approximately 9.4 nmi from the baseline's midpoint. (This approximate target distance, 9.4 nmi, is simply estimated from the chart using B = 10,084 feet.)

For the same target location and same phototheodolite pair, but using rigid quality-controlled film reading:

$$E = (0.49)(90) = 44 \text{ feet.}$$

From this, it is obvious that the more accurate data are obtained using film records, since film reading corrects for operator tracking error. The penalty, however, is in the film reading process which, for any substantial amount of data, may result in delays of several weeks.

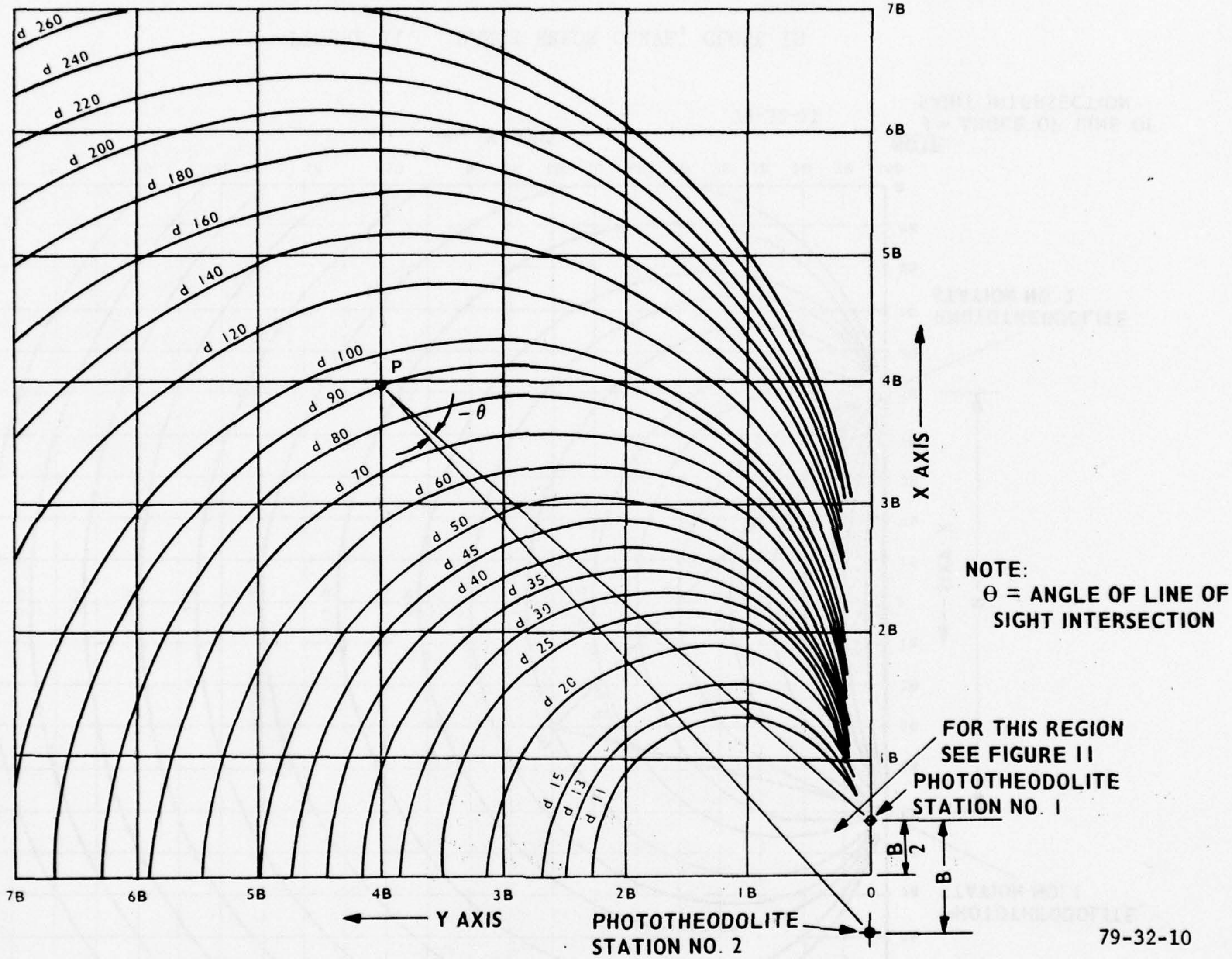


FIGURE 10. RANGE ERROR CURVE

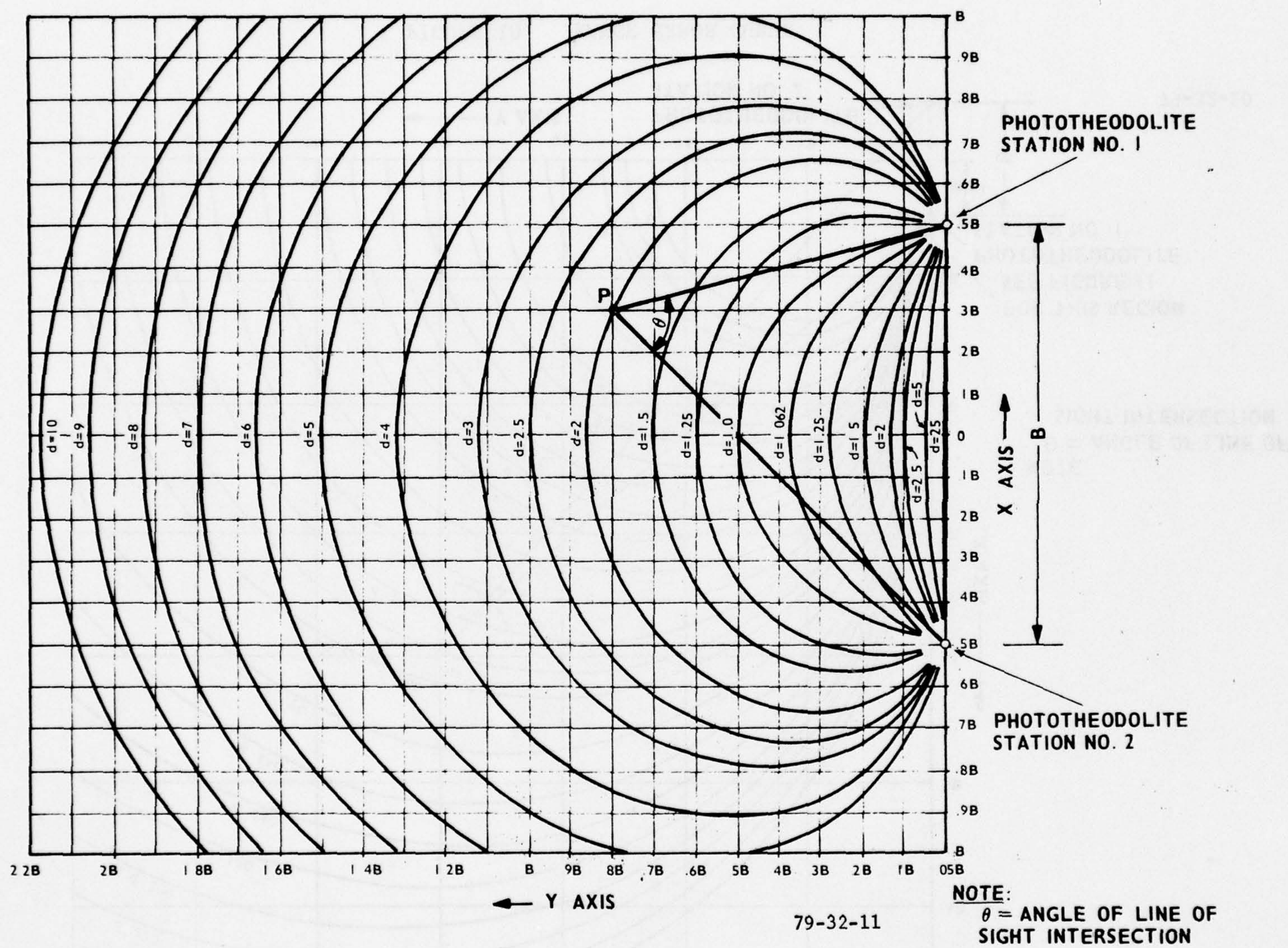


FIGURE 11. RANGE ERROR CURVE, CLOSE IN

Consider a point P (figure 11), where the target is close in, approximately 1.4 nmi from the baseline's midpoint. Using the same phototheodolite pair as in the previous example,

E = (4.38)(2) = 8.8 feet with magnetic tape data, and

E = (0.49)(2) = 0.98 feet using quality film reading.

It is to be emphasized that E is defined as the "maximum potential error," it is not necessarily the actual error that is obtained from each and every point measurement and computation of target position. This will be further described later. At this point, however, the charts are adequate in providing a quick estimate of maximum potential error for given baseline, data processing, and target location.

ERROR DEFINITION.

An expanded analysis of phototheodolite system error is given in the appendix.

FILM DATA VS. MAGNETIC TAPE DATA.

Tests of phototheodolite film data versus real-time magnetic tape data were conducted in 1973 and reported in FAA-RD-74-207, "Microwave Landing System Phase II Tracker Error Study." Phototheodolite system specifications are given in table 2. In this report, 10 runs were flown, with phototheodolites P8, P29, and P36 tracking. Film data, reduced using the standard film reading procedures, were compared with magnetic tape data.

A total of 2,612 samples of data were evaluated ranging from approximately 7,000 to 15,000 feet distant. The mean and standard deviation statistics of the differences in terms of MLS XYZ coordinates were as follows:

		ΔX	ΔY	ΔZ
mean	(ft)	3.42	1.54	1.12
std. dev.	(ft)	2.29	2.14	1.03

where Δ denotes magnetic tape data minus film data.

TABLE 2. PHOTOTHEODOLITE SPECIFICATIONS

LEADING PARTICULAR	CHARACTERISTIC
Phototheodolite Instrument	Contraves Model C
Maximum Range	15 nautical miles (nominal)
Photographic Film Size	35 millimeter
Azimuth or Elevation Tracking Velocity	33^{o} per second
Azimuth or Elevation Tracking Acceleration	60^{o} per second
Azimuth Range	360^{o}
Elevation Range	-5^{o} to 90^{o}
Data Sampling Rates	
Photographic film data	5 or 20 frames per second
Plotting board	5 samples per second
Computer format tape	20 samples per second
Tabulator	5 sets of coordinates per second
Real-time tabulator	5 sets of coordinates per second
Raw Data Recorder	
Type	Ampex Model FR 1100
Tape size	1/2 inch
Number of channels	7
Recording speed	7.5 inches per second
Recording time for a 2,400-foot roll of tape	1 hour
Computer Format Recorder	
Type	Ampex Model FR 1100
Tape size	1/2 inch
Channels	7
Recording speed	20.8 inches per second
Recording time for a 2,400-foot roll of tape	20 minutes
Coordinate Conversion Computer	
Full-Scale Output	
X or Y	100,000 feet
Z	25,000 feet
Plotting Board	
Size	30 inches by 30 inches
Area mode scales (maximum range)	
X-Y	100,000 feet
	50,000 feet
	25,000 feet
	10,000 feet
Z	0 to 20,000 feet
	0 to 10,000 feet
	0 to 5,000 feet
Encoders	
Azimuth elevation	15 bits
	LSB = 40 arc-seconds

EXTENDED AREA INSTRUMENTATION RADAR

The Model 661 EAIR is a precision C-band instrumentation radar system designed to measure, record, and display aircraft coordinates in slant range, azimuth, and elevation angles. Maximum tracking distance of the EAIR is 100 nmi in primary (skin) mode, and 190 nmi in secondary (beacon) mode, while minimum tracking distance is 1 nmi. Digital output data consisting of slant range, azimuth angle, and elevation angle are recorded on magnetic tape. Analog data in XY or XH (H = height above earth) coordinates are recorded real-time on a 30-inch plotter.

Photographs of the facility are shown in figures 12, 13, and 14. A diagram of the basic system is shown in figure 15.

The antenna is a 14-foot parabolic reflector with a beam width of 0.9° and selectable polarization, either linear or circular. The antenna can rotate through 360° horizontally, and from -1 1/2° through 90° in the vertical plane.

A 26 1/2-foot rigid foamed plastic radome protects the antenna and its pedestal from the elements. The antenna, azimuth, and elevation axes are driven by gearless direct current (d.c.) torque motors which drive direct-coupled, 17-bit digital data takeoffs.

Digital signals are applied to a digital data converter and magnetic tape recorder which also includes a NAFEC central time unit. The data are organized into a suitable format which is recorded on magnetic tape for subsequent processing on the NAFEC central computer.

The EAIR features: automatic tracking once the aircraft is acquired, which enables the radar antenna and range system to automatically follow aircraft movements; an aided range-tracking feature that enables a range gate to be set at aircraft velocity to facilitate angle lock-on or tracking during poor signal conditions; and raster scanning to assist in target acquisition. The EAIR also has the capability of providing or receiving synchronizing and slaving information to or from other radars or from phototheodolites.

DATA FLOW.

The EAIR (figure 16) (1) contains a tracking and recording system that includes an analog computer and digital data processor. Aircraft trajectory display of XY or XH coordinates is provided on a 30-inch x 30-inch plotter (2) which has continuously adjustable range scales from 6,000 to 400,000 yards. NAFEC central time (3) provides timing signals to the plotter and raw data tape (4).

The raw data tape contains time and raw radar measurements in slant range, azimuth, and elevation angles, plus quality bits for program check of time accuracy, designation whether the radar is in manual track or automatic

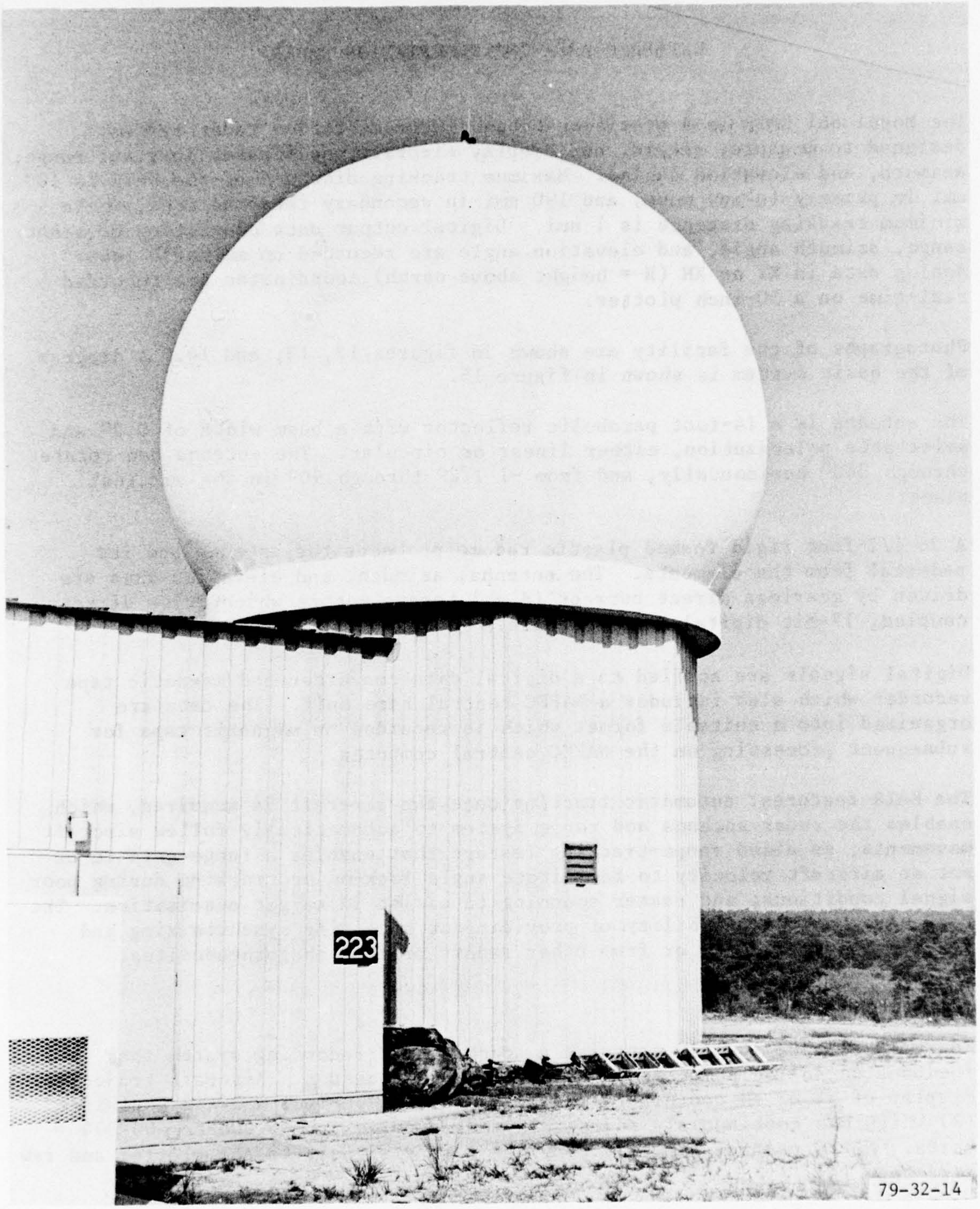


FIGURE 12. EAIR FACILITY

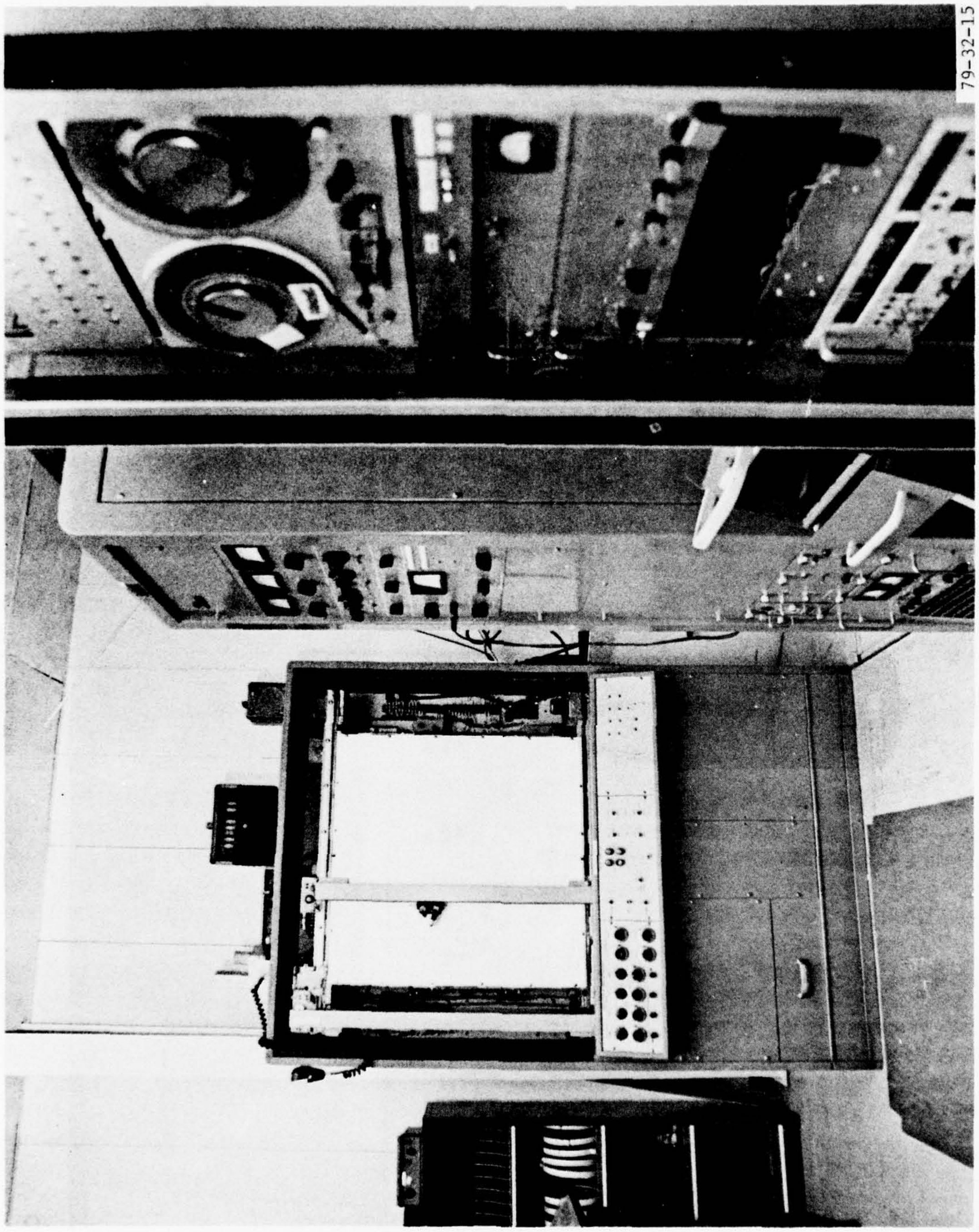


FIGURE 13. PLOTTER/RECORDER

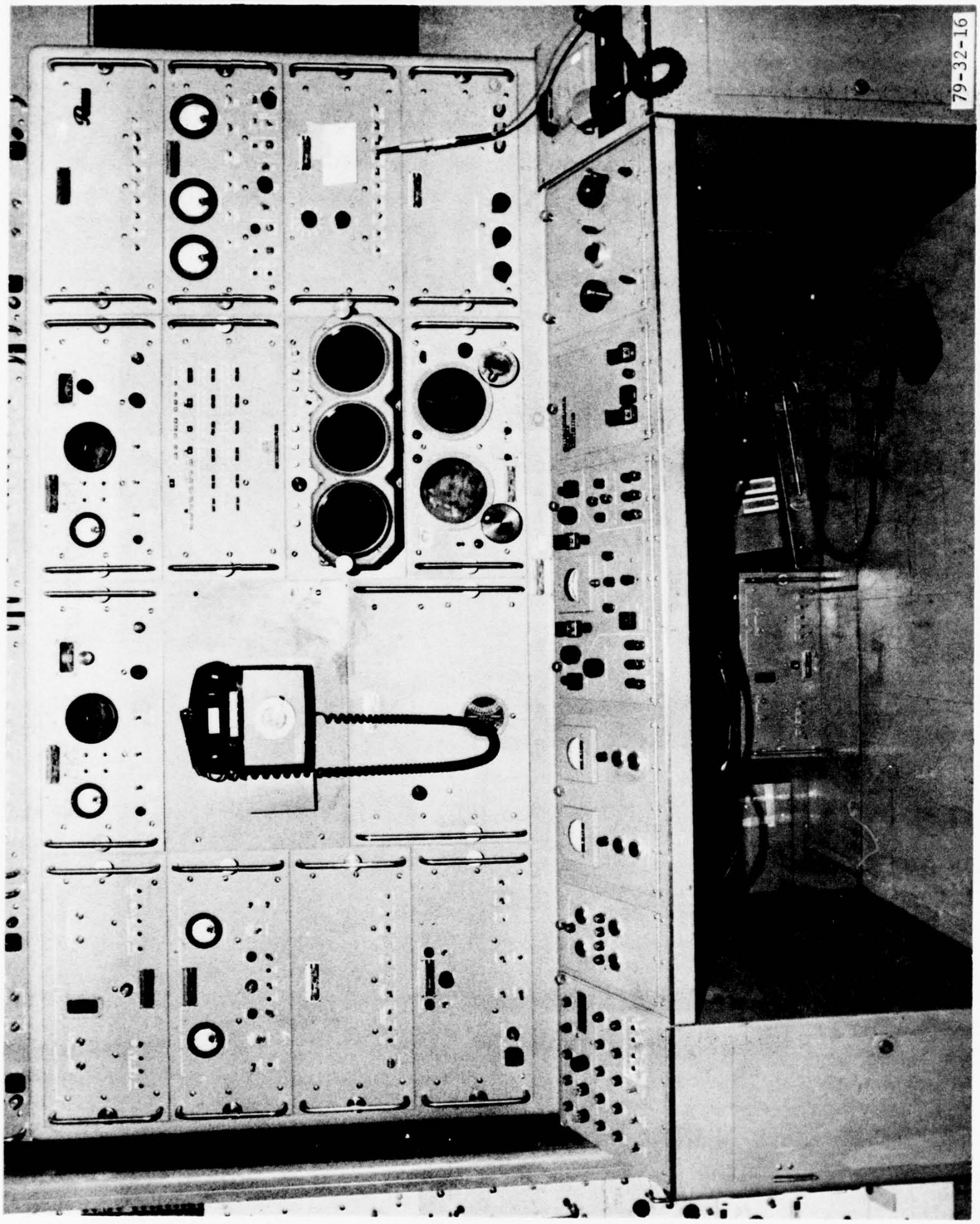


FIGURE 14. RADAR CONSOLE

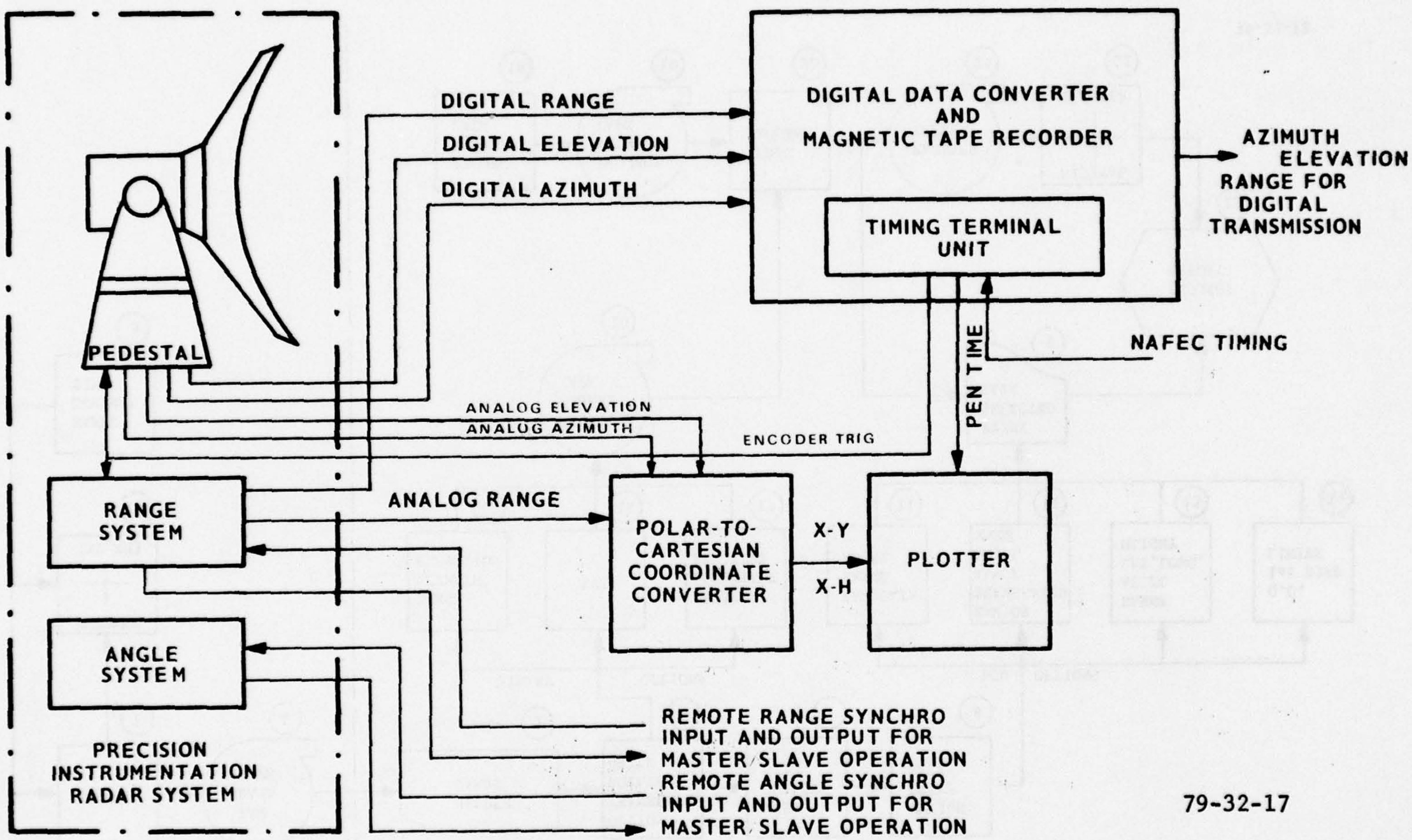
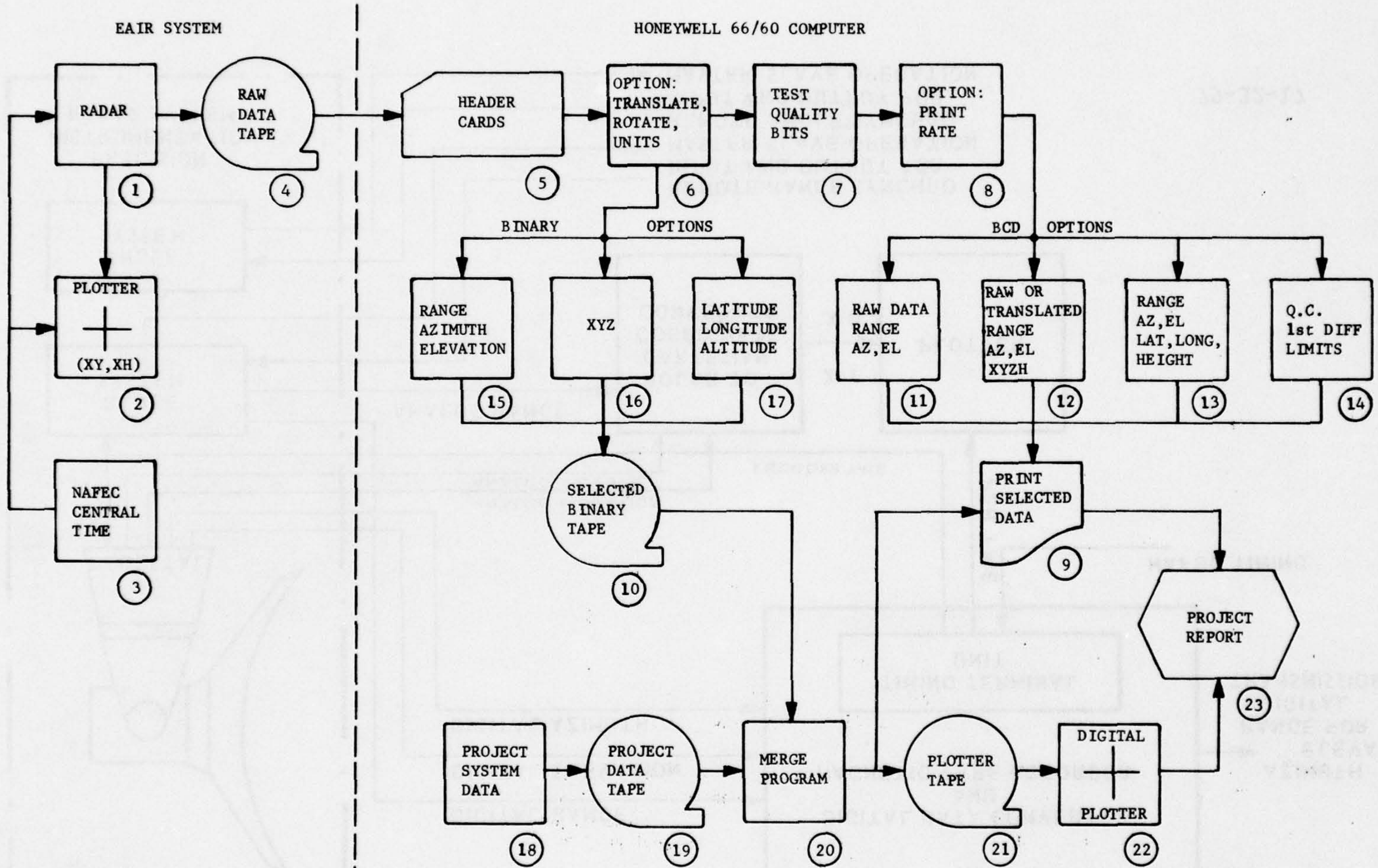


FIGURE 15. EAIR DIAGRAM



79-32-18

FIGURE 16. EAIR SYSTEM DATA FLOW

track, and other manually inserted information. Data recording rate is 10 samples per second.

EAIR raw data tapes are processed on the NAFEC computer using the EAIR production program. Header cards (5) or keyboard entries register identification information such as project title and number, tape number, and options instructions. Origin translation and rotation are entered as an option (6). The program accepts geodetic or cartesian coordinates of a new origin or orientation of axes.

Regardless of options selected, the program will always test EAIR quality bits (7), and will flag the absence of any quality bit by automatic insertion of a negative sign on each associated time word in which the quality bit is missing. These quality bits dropout when EAIR looses target track, when tracking manually, or when the time word is bad.

Printout rate is optionally selected (8) from a maximum rate of 10 samples per second to a minimum rate of one sample per minute.

Processed data from the EAIR program may be opted for a binary coded decimal (BCD) printout (9), a binary tape (10), or both.

Optional listings of processed EAIR data in the BCD printout are for the following groupings of target position coordinates: slant range, azimuth, elevation angles (11), XYZ and height (12); or slant range, azimuth and elevation angles, latitude, longitude, and height (13). Any or all of these options may be selected in a given program run. BCD printout of data (sample shown in figure 17) may satisfy project requirements with no further processing of data.

EAIR data quality is checked via a first-differences test (14) of consecutive range, azimuth, and elevation values. These first differences are compared with preestablished values, and values outside these limits are flagged and printed out separately.

Binary options permit data records in the following groupings: slant range, azimuth, and elevation (15), XYZ (16), or latitude, longitude, and height (17). Each tape also carries time of day.

Project system data, recorded on project instrumentation (18) in analog converted to digital, or on digital recording (19) are typically merged (20) with the EAIR binary tape. This merge program produces such outputs as comparative differences in azimuth (perhaps for comparison with project very high frequency omnirange (VOR) bearing measurements), or range (typically for comparison with distance measuring equipment (DME) measurements). Differences are treated statistically for a summarized printout (9), or a plotter tape (21) is generated to permit construction of plots on the NAFEC computer's digital plotter (22). Printouts and plots serve as basis from which the accuracies of project systems are determined. Plots frequently are incorporated in final reports (23).

			229-775-350 4-28-78 BINARY GOLDSER					PAGE 24
FAA-NAFEC EAIR'78		PROCESSED-11/29/78 RUN# 2 OF TAPE#R0386				TAPE DATE- 4/28/78		
			EAIR RAW DATA AND X Y Z COORDINATES					
TIME	AZIMUTH	ELEVATION	RANGE	X	Y	Z	HEIGHT	
54307.5 15 5 7.5	209.894	3.197	241722.000	-120285.277	-209234.908	13583.740	14976.750	
54307.6 15 5 7.6	209.894	3.197	241758.000	-120303.191	-209266.070	13585.747	14979.000	
54307.7 15 5 7.7	209.894	3.197	241794.000	-120321.105	-209297.232	13587.755	14981.750	
54307.8 15 5 7.8	209.894	3.197	241836.000	-120342.006	-209333.588	13590.097	14984.500	
54307.9 15 5 7.9	209.894	3.197	241872.000	-120359.920	-209364.748	13592.105	14986.750	
54308.1 15 5 8.1	209.894	3.197	241914.000	-120380.820	-209401.104	13594.447	14989.750	
54308.1 15 5 8.1	209.897	3.197	241950.000	-120408.773	-209426.494	13596.455	14992.000	
54308.2 15 5 8.2	209.897	3.197	241986.000	-120426.689	-209457.654	13598.463	14994.250	
54308.3 15 5 8.3	209.897	3.197	242022.000	-120444.605	-209488.816	13600.470	14997.250	
54308.4 15 5 8.4	209.897	3.197	242064.000	-120465.507	-209525.170	13602.813	14999.750	
54308.5 15 5 8.5	209.899	3.197	242106.000	-120496.454	-209555.748	13605.155	15002.750	
54308.6 15 5 8.6	209.899	3.197	242142.000	-120514.371	-209585.908	13607.163	15005.250	
54308.7 15 5 8.7	209.899	3.197	242178.000	-120532.288	-209618.068	13609.170	15007.500	
54308.8 15 5 8.8	209.899	3.197	242220.000	-120553.192	-209654.422	13611.513	15010.250	
54308.9 15 5 8.9	209.902	3.197	242256.000	-120581.161	-209679.801	13613.521	15012.750	
54309.1 15 5 9.1	209.902	3.197	242292.000	-120599.079	-209710.961	13615.528	15015.000	
54309.1 15 5 9.1	209.902	3.197	242334.000	-120619.984	-209747.313	13617.870	15018.000	
54309.2 15 5 9.2	209.902	3.194	242376.000	-120641.213	-209784.227	13608.612	15009.250	
54309.3 15 5 9.3	209.902	3.194	242412.000	-120659.132	-209815.385	13610.618	15011.500	
54309.4 15 5 9.4	209.902	3.194	242454.000	-120680.037	-209851.738	13612.958	15014.500	
54309.5 15 5 9.5	209.902	3.194	242490.000	-120697.955	-209882.896	13614.964	15017.000	
54309.6 15 5 9.6	209.902	3.194	242526.000	-120715.874	-209914.057	13616.970	15019.000	
54309.7 15 5 9.7	209.902	3.194	242568.000	-120736.779	-209950.408	13619.311	15022.250	
54309.8 15 5 9.8	209.902	3.194	242604.000	-120754.698	-209981.568	13621.317	15024.500	
54309.9 15 5 9.9	209.902	3.194	242646.000	-120775.604	-210017.920	13623.657	15027.250	
54310.1 15 5 10.1	209.902	3.194	242682.000	-120793.522	-210049.080	13625.663	15030.000	
54310.1 15 5 10.1	209.902	3.194	242730.000	-120817.414	-210090.625	13628.338	15033.000	
54310.2 15 5 10.2	209.902	3.194	242754.000	-120829.360	-210111.398	13629.675	15034.750	
54310.3 15 5 10.3	209.902	3.194	242802.000	-120853.252	-210152.943	13632.350	15038.000	
54310.4 15 5 10.4	209.902	3.194	242838.000	-120871.171	-210184.102	13634.356	15040.000	
54310.5 15 5 10.5	209.902	3.186	242874.000	-120890.059	-210216.947	13601.488	15007.500	
54310.6 15 5 10.6	209.902	3.186	242922.000	-120913.950	-210258.492	13604.156	15011.000	
54310.7 15 5 10.7	209.902	3.186	242952.000	-120928.883	-210284.459	13605.823	15013.000	
54310.8 15 5 10.8	209.902	3.183	242994.000	-120950.110	-210321.371	13596.527	15004.500	
54310.9 15 5 10.9	209.902	3.183	243030.000	-120968.029	-210352.531	13598.525	15006.750	
54311.1 15 5 11.1	209.902	3.183	243072.000	-120988.936	-210388.885	13600.858	15009.500	
54311.1 15 5 11.1	209.902	3.183	243108.000	-121006.854	-210420.043	13602.857	15011.750	
54311.2 15 5 11.2	209.902	3.183	243150.000	-121027.760	-210456.396	13605.190	15014.500	
54311.3 15 5 11.3	209.902	3.183	243186.000	-121045.679	-210487.557	13607.189	15017.500	
54311.4 15 5 11.4	209.902	3.183	243222.000	-121063.598	-210518.715	13609.188	15019.500	
54311.5 15 5 11.5	209.902	3.183	243264.000	-121084.503	-210555.068	13611.520	15022.250	
54311.6 15 5 11.6	209.902	3.183	243300.000	-121102.422	-210586.229	13613.519	15024.500	
54311.7 15 5 11.7	209.902	3.183	243342.000	-121123.327	-210622.580	13615.851	15027.500	
54311.8 15 5 11.8	209.902	3.183	243378.000	-121141.246	-210653.740	13617.850	15030.250	
54311.9 15 5 11.9	209.902	3.175	243414.000	-121160.133	-210686.582	13584.898	14997.500	
54312.1 15 5 12.1	209.902	3.175	243462.000	-121184.025	-210728.129	13587.556	15001.000	
54312.2 15 5 12.2	209.902	3.175	243534.000	-121219.863	-210790.447	13591.544	15005.500	
54312.3 15 5 12.3	209.902	3.175	243570.000	-121237.782	-210821.607	13593.538	15008.000	
54312.4 15 5 12.4	209.902	3.175	243612.000	-121258.688	-210857.961	13595.864	15011.000	
54312.5 15 5 12.5	209.902	3.172	243648.000	-121276.930	-210889.682	13586.197	15001.750	
54312.6 15 5 12.6	209.902	3.172	243690.000	-121297.836	-210926.035	13588.521	15004.250	

79-32-19

FIGURE 17. SAMPLE EAIR DATA LISTING

SYSTEM ACCURACY.

A limited test of system accuracy was conducted and reported in report FAA-NA-73-94, entitled, "Accuracy Test of NAFEC Instrumentation Radar." This report showed raw range errors to be 161 feet, which, corrected for propagation, reduced to 96 feet, of which there was an uncertainty of 27 feet in the photographic reference positioning system used in the test to establish true position.

Reference position data for this test were collected using a Type K-38 aerial camera, with 36-inch focal length and 9 x 18 negative. Terrain photographs were taken of prominent structures; in this case, tall buildings in central Philadelphia. Since vertical objects in photographs taken at altitude tend to lean away from the aircraft's plumb point at the instant the photo was taken, tracing several such leaning lines resulted in a crossing point on the film which established plumb point. Detailed maps were then used to read aircraft position in geodetic coordinates, which were recomputed in the radar parameters of slant range and azimuth. From time-correlated EAIR measurements, comparisons of slant range and azimuth provided the results shown in table 3.

The previously referenced report, "Microwave Landing System Phase II Tracker Error Study," notes the following EAIR data characteristics: "There existed very large bias and low-frequency differences between EAIR and phototheodolite position data...there is a variation of range error with distance from the EAIR location."

Table 4 lists summary statistics of EAIR beacon data versus phototheodolites resulting from the MLS flight test program. Figure 18 is a plot of data from runs in this test. It shows an oscillation in slant range error that was found to be both repeatable and predictable. The MLS program established an error equation to offset the cyclic error, which is described in this report. In general, however, the means and standard deviations of range error were comparable to those obtained in the previously described 1966 EAIR test.

EAIR system specifications are given in table 5.

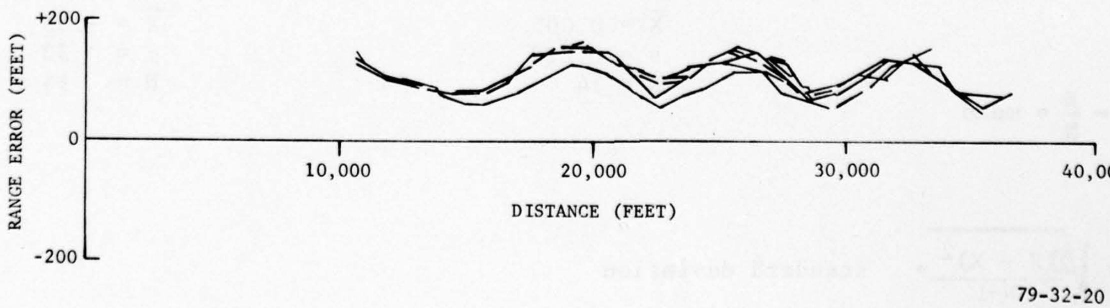


FIGURE 18. EAIR RANGE ERROR

TABLE 3. EAIR SUMMARY STATISTICS

SKIN TRACK	AZIMUTH (DEGREES)			RANGE (FEET)		
TIME	PHOTO (P)	EAIR (E)	AZ (P-E)	PHOTO (P)	EAIR (E)	R (P-E)
1001:5012	319.125	319.142	-.017	241,721	241,806	- 85
1024:22.1	319.290	319.271	+.019	241,830	241,926	- 96
1031:41.7	319.136	319.153	-.017	242,558	242,766	-208
1038:44.8	319.187	319.175	+.012	242,246	242,310	- 64
1045:05.0	319.168	319.208	-.040	241,579	241,668	- 89
1052:04.5	319.250	319.249	+.001	242,136	242,214	- 78
1057:21.9	319.082	319.098	-.016	242,166	242,310	-144
1109:11.2	319.058	319.084	-.026	242,321	242,466	-145
1121:07.8	319.128	319.158	-.030	241,937	242,082	-145
1127:15.7	319.306	319.309	-.003	241,633	241,710	- 77
			$\overline{X}$ = -0.012			$\overline{X}$ = -113
			s = 0.019			s = 45
			N = 10			N = 10
BEACON TRACK						
1354:46.4	319.090	319.098	-.008	242,135	242,298	-163
1407:17.0	319.105	319.109	-.004	242,026	242,196	-170
1412:38.7	319.250	319.221	+.029	242,040	242,166	-126
1417.43.1	319.055	319.065	-.010	242,279	242,484	-205
1423:44.4	319.266	319.246	+.020	242,011	242,172	-161
1428:28.2	319.054	319.073	-.019	242,361	242,514	-153
1434:38.4	319.164	319.139	+.025	242,579	242,742	-163
1439:55.5	319.075	319.095	-.020	242,252	242,430	-178
1445:37.5	319.172	319.112	+.060	242,520	242,682	-162
1457:26.5	319.313	319.296	+.017	241,745	241,854	-109
1502:01.6	319.101	319.109	-.008	242,287	242,384	- 97
1509:00.3	319.161	319.164	-.003	242,679	242,838	-159
1513:54.8	319.060	319.073	-.013	242,320	242,514	-194
1525:04.4	319.055	319.051	+.004	242,322	242,538	-216
			$\overline{X}$ = 0.005			$\overline{X}$ = -161
			s = 0.023			s = 33
			N = 14			N = 14

$\overline{X} = \frac{X}{N}$ = mean

$s = \sqrt{\frac{\Sigma(X - X)^2}{N-1}}$ = standard deviation

TABLE 4. EAIR VS. PHOTOTHEODOLITE, RAW DIFFERENCES

Run No. (all on 9/27/73)	Distance Partition-SMLS (ft)		Range Difference (ft)		Azimuth Difference (milliradians)		Elevation Differences (milliradians)	
	Start	Stop	$\overline{X}$	s	$\overline{X}$	s	$\overline{X}$	s
3	24990.	21994.	102.45	23.02	0.24	0.42	-0.51	0.18
	21994.	19117.	136.97	24.41	0.43	0.77	-0.58	0.24
	18987.	15857.	128.18	21.27	0.90	1.03	-0.68	0.42
	15989.	12816.	87.20	10.11	1.77	1.20	-0.77	0.70
	12995.	9887.	124.55	21.18	3.03	1.97	1.79	4.39
4	33994.	30584.	135.15	20.33	0.02	0.48	-0.44	0.26
	30999.	27561.	101.12	24.61	0.18	0.34	-0.37	0.14
	27988.	24680.	144.65	19.89	0.23	0.41	-0.37	0.21
	24988.	21380.	114.37	16.28	0.18	0.51	-0.47	0.24
	21983.	18102.	147.76	21.28	0.45	0.61	-0.60	0.20
	19018.	15879.	130.14	33.79	1.56	7.96	-0.62	0.42
	15986.	12364.	91.22	9.19	2.35	1.73	-0.95	0.54
	12981.	9684.	121.91	19.28	3.48	3.38	2.49	4.59
5	36983.	33609.	88.77	21.00	0.03	0.45	-0.39	0.20
	33981.	30716.	123.91	28.48	-0.07	0.35	-0.38	0.13
	30985.	27812.	94.80	22.06	0.16	0.38	-0.45	0.16
	27995.	24948.	138.69	16.39	0.32	0.40	-0.41	0.15
	24993.	21914.	115.77	14.83	0.30	0.56	-0.41	0.25
	21989.	18932.	146.27	21.39	0.50	0.82	-0.64	0.23
	18990.	15859.	127.61	23.37	0.86	0.82	-0.56	0.19
	16000.	12884.	86.22	6.33	2.16	0.94	-0.69	0.43
	12999.	9798.	118.42	19.40	2.53	3.00	1.76	4.06

TABLE 5. EAIR SPECIFICATION

LEADING PARTICULAR	CHARACTERISTIC
Radar	
Transmitter	
Frequency	C-Band, 5450 to 5825 megacycles
Magnetron	Tunable, type 7156
Peak Power Output	1/4 megawatt (double or triple pulse capability)
Pulse Repetition Frequency	410 pulses per second
Pulse Duration	0.8 microsecond
Antenna	
Reflector	14-foot parabolic
Scanner Polarization (Remote Selectable)	Linear vertical Linear horizontal Right-hand circular Left-hand circular
Gain	45 dB
Side Lobe Level	At least -22 dB referred to peak of main lobe
Static Beamwidth	0.9
Crossover	80%
Dynamic Beamwidth	1.39 at 80% crossover
Nutation Rate	1,800 rpm
Antenna Positioning	
Elevation (El)	-1 1/2 and -181 1/2
Azimuth (Az)	Continuous 360
Limit Settings (Elevation)	-3 and 183 (beginning of energy absorption--absolute limits -8 and 188)
Electrical	-1 1/2 and -181 1/2. With excess speed, auxiliary limits at 7 and 173
Modes-Manual incl. raster	Manually positioned synchros and followups
Remote	Controlled by one speed synchro information from remote source
Automatic	Controlled by radar error signal generated by 30-cycle conical scan. Double integration of error signal to provide tracking with negligible velocity error and acceleration constant depending on smoothing setting. Separate selection of modes for azimuth and elevation possible for test or operations.
Az and El accuracy	0.2 milliradian (0.011°)

TABLE 5. EAIR SPECIFICATIONS (Continued)

LEADING PARTICULAR	CHARACTERISTIC
Receiver System	
Amplifier	Tunnel Diode
Minimum Discernible Signal	-104 decibels per 1 milliwatt (dBm)
Noise Figure	Less than 5.0 dB
AGC Dynamic Range	Minimum of 65 dB with 25 dB inserted manually for total of 90 dB
Beacon Delay	Continously variable 0-600 yards delay of tracking gate
General	Dual local oscillators permit simultaneous radar and beacon tracking, radar automatic frequency control (AFC) circuit referenced to transmitted frequency, beacon AFC circuit references to received signal
Range System	
Master Timing	81.946 kHz crystal-controlled oscillator (one in use, one standby). Temperature stability of crystals is better than 0.1 part/million/degree centigrade. Crystals are mounted in ovens having temperature stability of $\pm$ 1° centigrade
Range Calibration Accuracy	2 yards
Automatic Range Tracking Rate	10,000 yards/second
Manual Range Tracking Slew Rate	40,000 yards/second
Tracking Accuracy Range	With 12 dB signal-to-noise ratio, RMS error will not exceed 20 yards, exclusive of beacon or propagation errors at 3,000 yard/second range rate. Will track at range rates up to 10,000 yard/second with less than 50 yards range error.
Angle	Acceleration lags are defined by the acceleration constants. RMS tracking at signal-to-noise ratio of 18 dB will be about 0.15 mil RMS for low acceleration conditions. The radar will perform automatic tracking at rates up to 50 per second.
Maximum Range Skin Track	100 nautical miles
Beacon Track	190 nautical miles
Maximum Tracking Rate	5,000 miles per hour

TABLE 5. EAIR SPECIFICATIONS (Continued)

LEADING PARTICULAR	CHARACTERISTIC
Plotting Board Size	30 x 30 inches
Time Mark Intervals from Range Control Central	1 PPS and 1 PP10S
Map Scales	Continuously adjustable from 200 yards/inch to 40,000 yards/inch
Polar-to-Cartesian Coordinate Converter	
Maximum Range	400,000 yards
Parallax Adjustments	
X and Y	0-50,000 yards
H	0-10,000 yards
Earth Curvature Correction	Provided for both range and height
Outputs (X, Y and H)	d.c. voltage to plotting boards
Digital Data Converter Magnetic Tape Data	
Range Word	18-bit natural binary represents 400,000 yards of range to a resolution of 2 yards
Azimuth and Elevation Word	17-bit natural binary represents 360 of angle to a resolution of better than 10 seconds of arc
Time Word	24-bit BCD represents hours, minutes, seconds, to a resolution of 0.1 second.
Auxiliary Word	27-bit front-panel switch selectable
Computer Format Recorder	
Type	Kennedy Digital Tape Recorder
Magnetic Tape Running Time (Full Reel)	Approximately 6 hours
Tape Width	1/2 inch
Recording Rate	75 inches per second
Number of Tracks	7
Sampling Rate	10 samples per second (1 word consists of 20 samples)

LASER TRACKER

The precision automated tracking system is a mobile facility which uses an invisible laser beam to illuminate and automatically track cooperative targets. A retroreflector (figure 24) is required on the target aircraft.

The equipment, including very high frequency (VHF) communications and telemetry is mounted in a van for mobile operation as shown in figures 19 through 22. Power requirements are 208 volts, 3-phase, 60 hertz (Hz), at 45 kilowatts (kW).

The laser system consists of a target tracking subsystem that maintains automatic target track, and a data processing subsystem that processes, displays, and records tracking data.

The tracking subsystem contains:

- -Laser transmitter
- -Laser power supply
- -Laser receiver
- -Optical automatic gain control (AGC) system
- -System control
- -Range computer
- -Optical mount and servo system
- -Video optical sighting subsystem.

OPERATION.

The laser transmitter and optical receiver are mounted on an elevation-over-azimuth tracking mount as shown in figure 23. The transmitter emits short bursts of infrared laser energy in a very narrow beam. These pulses strike an optical reflector (figure 24) mounted on the target aircraft, return to a receiving telescope, and are processed by the receiver to produce azimuth and elevation pointing error signals. These error signals are used to drive servo motors that move the optical mount in azimuth and elevation to maintain automatic target tracking. Range is obtained by measuring the time interval between transmitted and received optical pulses. Range, azimuth, and elevation in digital format are supplied to the data processing subsystem.

The laser transmitter consists of a laser resonator which generates the laser beam. The laser beam from the transmitter passes through the following optical elements:

1. An optical AGC attenuator assembly which can insert up to 60 decibels (dB) of attenuation into the beam path,

2. Beam-collimating optics which expand the laser beam diameter to approximately 1 inch, and

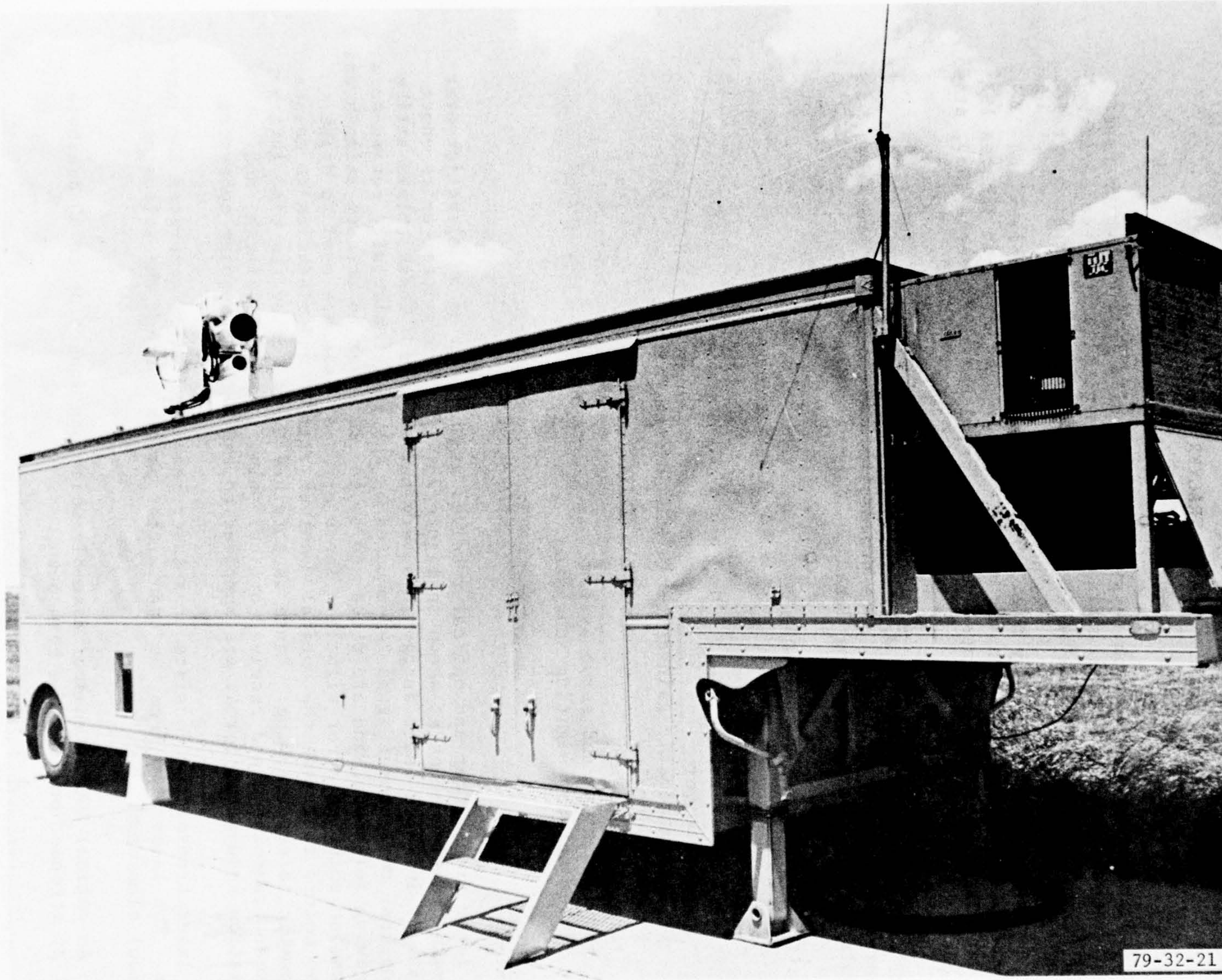


FIGURE 19. LASER VAN (SIDE)

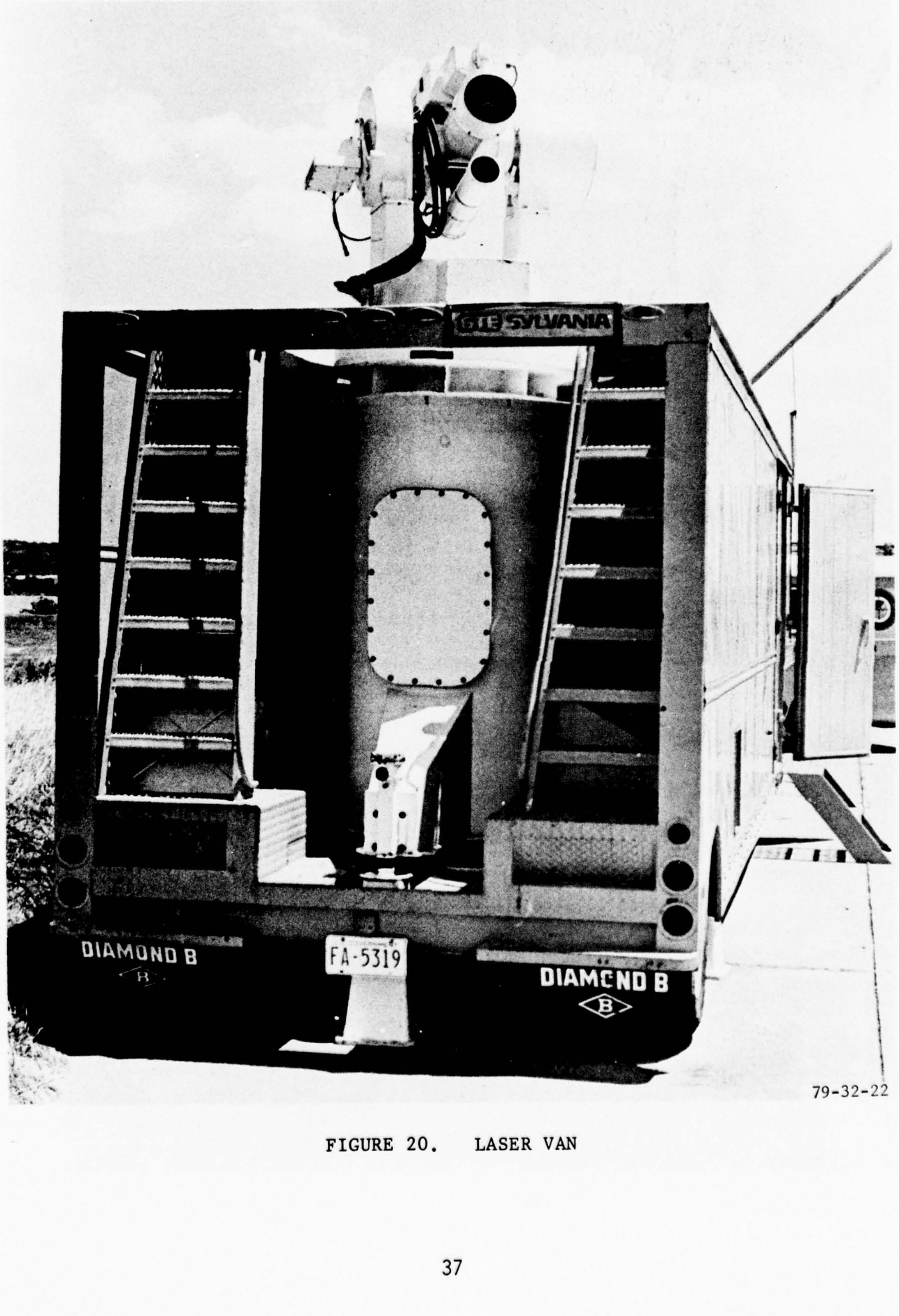


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FIGURE 20. LASER VAN

FIGURE 21. VAN INTERIOR

FIGURE 22. VAN INTERIOR

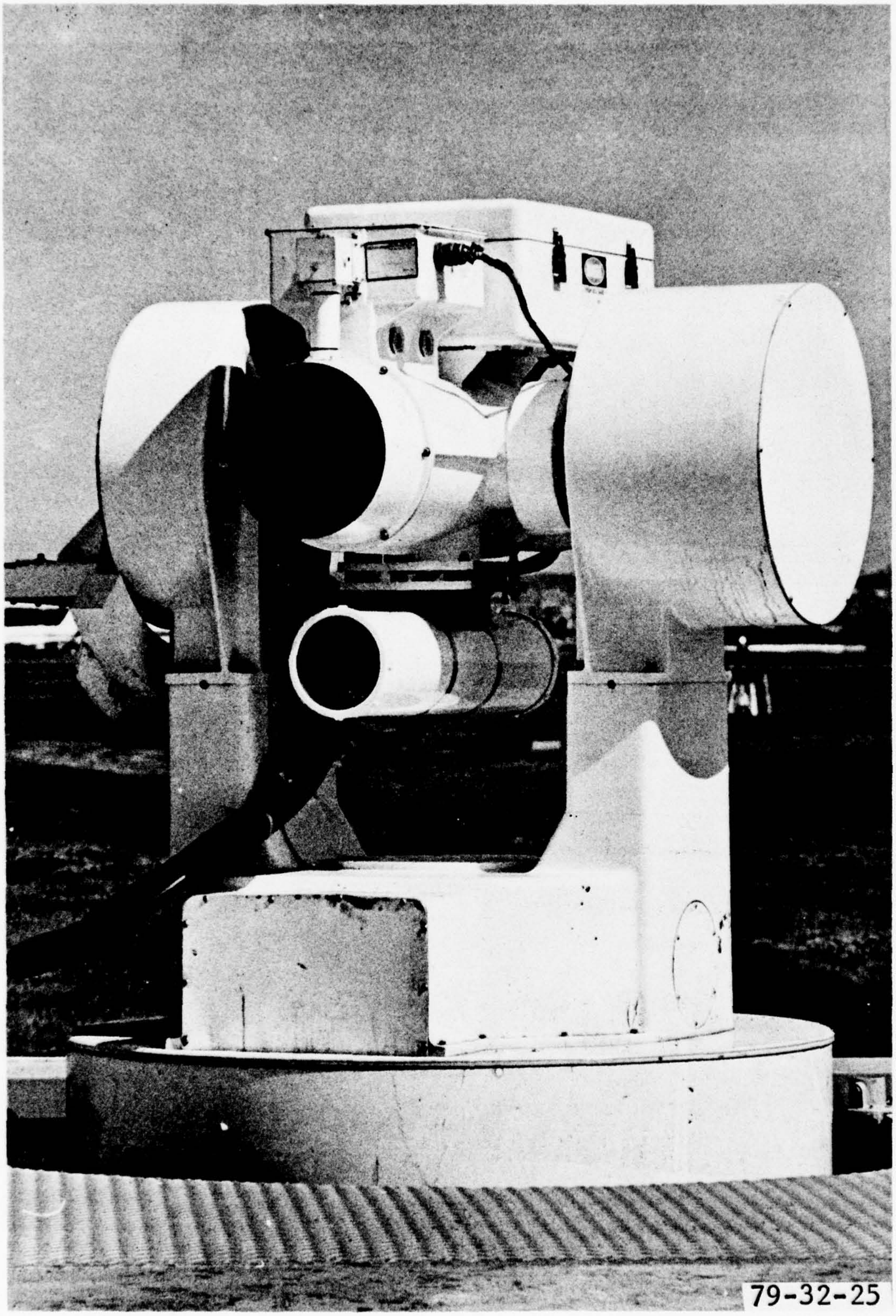

FIGURE 23. OPTICAL PACKAGE

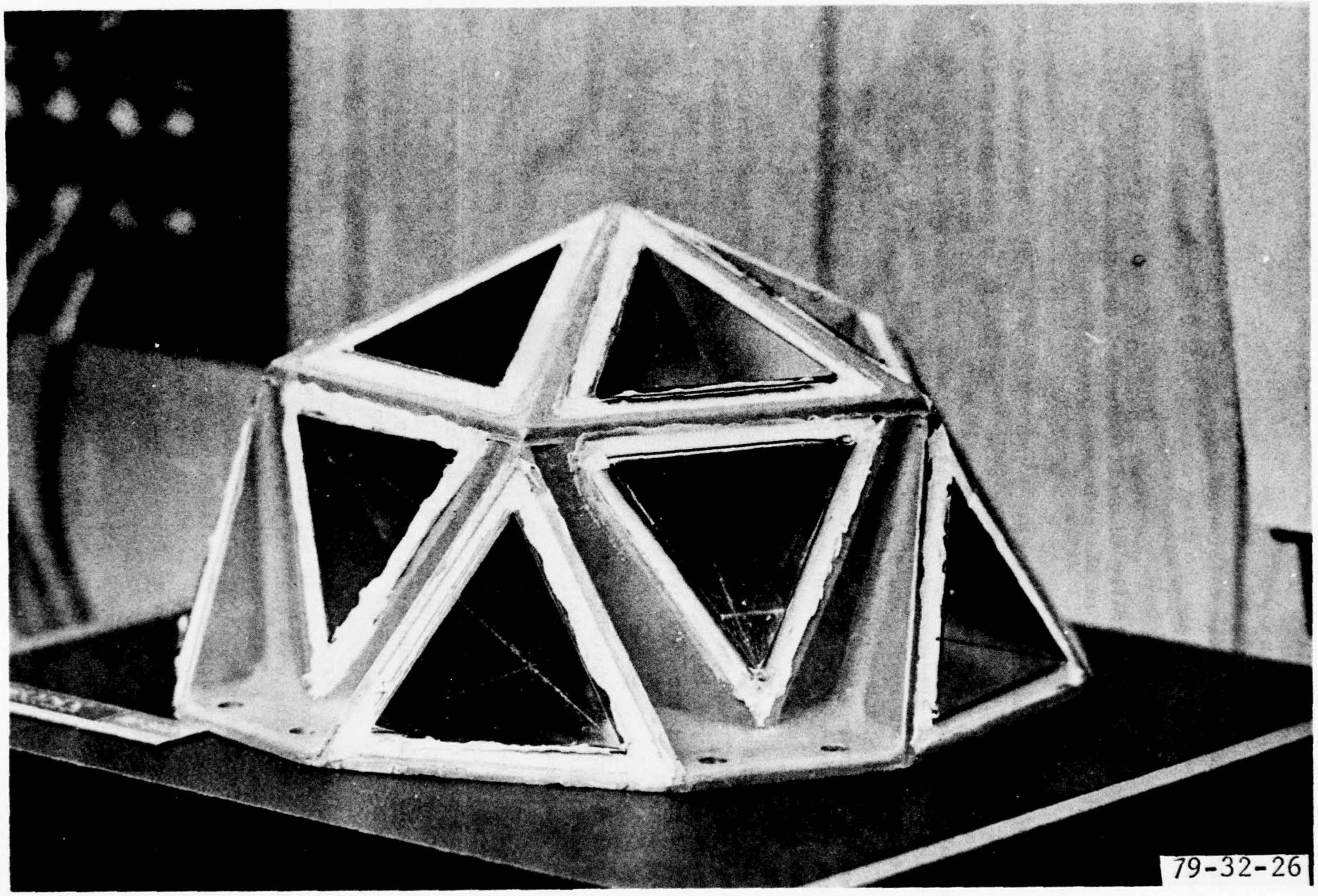

FIGURE 24. RETROREFLECTOR

3. Prisms which direct the collimated laser beam to the center of the receiving telescope and align the beam coaxial with the telescope optical axis.

The laser resonator is basically an oscillator that operates at the wavelength of 1.064 microns in the near-infrared region of the optical spectrum.

Target returns are captured by a conventional 8-inch diameter Schmidt-Cassegrain telescope which has an effective focal length of 66 inches and an aperture of f/8.25. The telescope's optical output is directed to a 4-quadrant photodetector. When the telescope axis is pointed precisely at the tracked target, all quadrants of the photodetector receive equal portions of the target return image, and the detector outputs are equal. When the target is slightly off axis, the detector outputs are unequal and are a function of the magnitude and direction of the pointing error. Outputs of the photodetector are processed to develop error signals to the optical mount servo system.

A narrow-band optical bandpass filter, centered at the laser beam wavelength and positioned between the telescope output and the quadrant photodetector, discriminates against ambient visible light sufficiently to reduce sky background noise at the photodetector below the inherent noise level of the detector.

An optical AGC system operates a filter wheel in conjunction with transmitter optical attenuators to maintain constant average optical signal levels at the quadrant photodetector.

Range measurement is made by an interval counter that starts when the laser fires and stops upon receipt of a target return pulse. The range computer is initialized each time the laser is fired, and the interval counter starts approximately 200 microseconds (μs) later. If no target return pulse is received, the interval counter will count to overflow, causing a signal which the computer uses to disregard that data sample.

Range to the tracked target is measured and displayed with a resolution of 1 foot. The range word is in 18-bit parallel binary format and is supplied to the data processing subsystem at a 100-per-second sample rate.

The optical mount is mounted on a three-legged pedestal that is bolted to the trailer frame for transport. When tracking, the pedestal is mechanically isolated from the trailer. For leveling purposes, the mount is equipped with levels that have a resolution of five arc-seconds.

Video-optical sighting equipment allows targets of interest to be acquired visually, after which the system switches to an autotrack mode. The video portion of the target acquisition uses a television camera that is mounted below the receiving telescope and aligned with the tracking optical axis. The optical portion of the target acquisition equipment consists of a remote

acquisition aid which is basically a six-power telescope, with an 8° field of view, mounted on a small elevation-over-azimuth pedestal.

Single-speed torque synchro transmitters send azimuth and elevation pointing angles to the computer interface unit where they are converted to digital format. The computer software program generates drive commands to the optical mount to move the mount to the azimuth and elevation angles of the acquisition aid to acquire a target sighted in the telescope.

DATA PROCESSING SUBSYSTEM.

This system contains:

- central processing unit
- extended arithmetic unit
- magnetic core memory
- alphanumeric terminal
- magnetic tape units
- magnetic disk drive
- paper tape reader/punch
- card reader
- line printer
- teletypwriter
- graphic terminal
- XY plotter.

During a tracking mission, the data processing subsystem operates online to exercise control over the tracking subsystem while formatting tracking data for recording and display.

The data processing subsystem contains a Digital Equipment Corp. PDP-11/35 processor and associated peripherals. A unibus interconnects peripherals to the central processing unit and to each other for data transfer and control.

The alphanumeric terminal in the control console (figure 25) is the primary interface between the operator and the data processing subsystem. It consists of a keyboard and a 10-inch CRT. During pre-mission initialization, the terminal functions as a normal teletypewriter to enter various mission parameters. After a tracking mission, track data recorded on magnetic tape may be dumped onto the display for rapid visual editing.

Magnetic tape units consist of one nine-track tape and two seven-track units, with all three tape drives sharing the same controller interface. Although the nine-track unit is designated the "master" and the others "slave," each transport is equally accessible to the computer.

The magnetic disk subsystem is capable of holding over 1.2 million words of random access storage space. This large storage capability allows all system programs, compilers, assemblers, etc., to be online and rapidly transferred

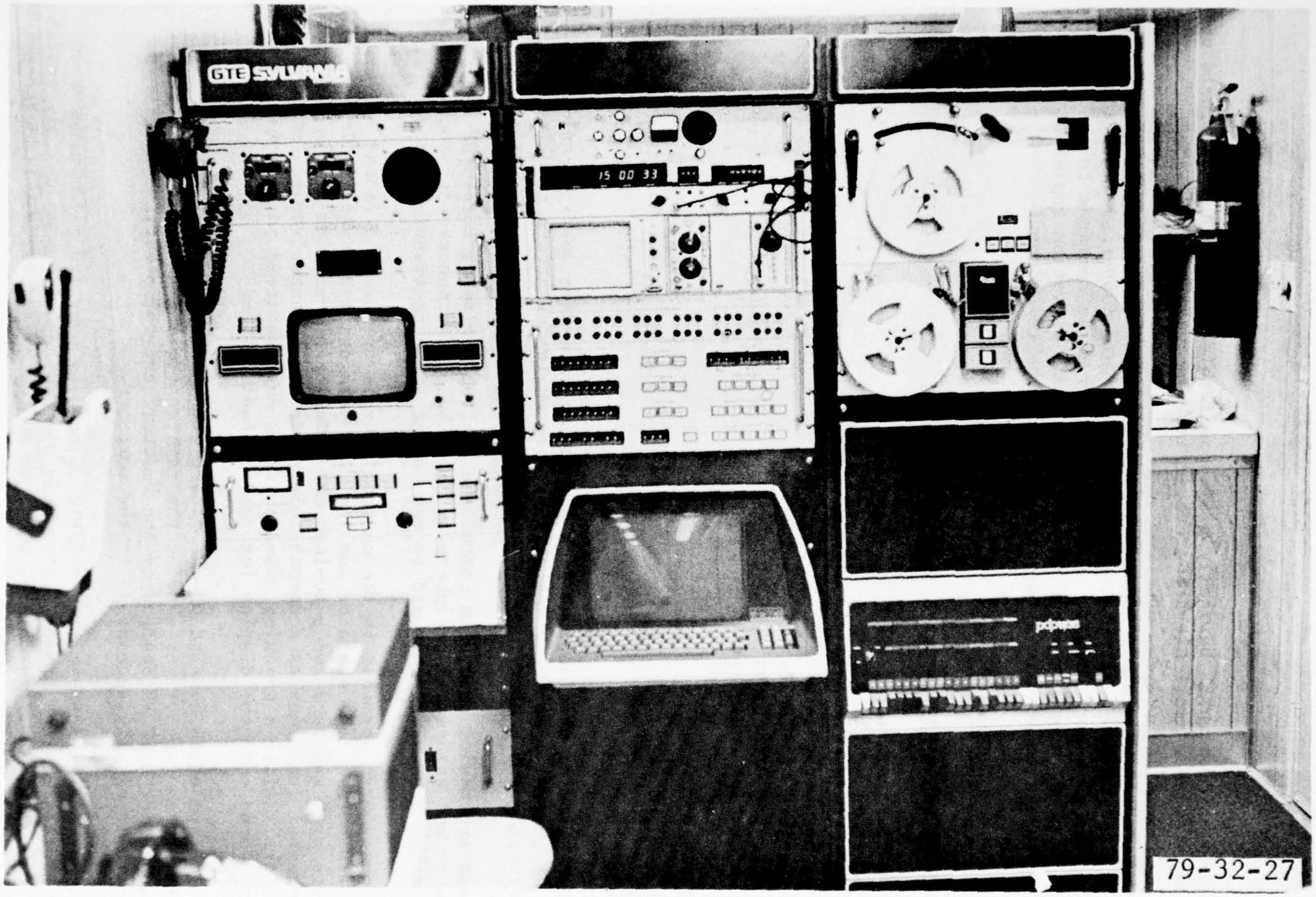

FIGURE 25. CONTROL CONSOLE

to core for execution. Magnetic core memory provides space for storing 32K words.

DATA FLOW.

In figure 26, the laser facility (1) receives NAFEC central time from a time code generator (2) synchronized to NAFEC time. Prior to a flight mission, target board calibration data (3) are measured and recorded, and a rate of data recording (4) is selected (between 1 and 100 samples per second; usually 10 per second).

The raw data tape (5) of range, azimuth, elevation, time, and 15 quality bits is delivered to the computer complex for processing. Initially, control cards are prepared (6) which permit insertion of title for printout, date, run numbers, coordinates of selected origin, data rate in and out, form of output data, whether binary tape is required and other options.

Target board calibration data (7) are used to calculate elevation encoder bias and tilt in direction and magnitude, which is applied to all elevation measurements, and the azimuth offset of the laser heading with respect to selected coordinates.

Quality bits (8) are tested, processed, and printed; these bits contain information on azimuth-elevation limits of the optical mount, radiated power level, and indicators for signal presence, automatic track or manual, computer responsible, remote acquisition, range overflow, acquisition data, laser transmitter on/off, and provision for a manually inserted event mark on the tape.

Azimuth and elevation error corrections signals (9) determined by the quadrant detector are digitized, recorded, and applied to azimuth and elevation measurements.

Translation and rotation of origin (10) is accomplished from input coordinates of the new origin, and data rates for data in and data out is established (11).

BCD tapes provide listings of range, azimuth, elevation, azimuth error correction, elevation error correction, and quality bits in a raw data tape (12), and for range, azimuth, elevation, XYZ and quality bits in the standard output tape (13) which are listed on the printer (14). A sample printout of laser data are shown in figure 27.

Binary tapes provide data in format common to the EAIR and phototheodolite binary tape formats. Presently, data in range, azimuth, elevation (15), in XYZ (16), or geodetic coordinates (17) are available.

The binary tape (18) is used generally in a merge program (19) with data from a project system (20) which produces a project tape (21). The merge program

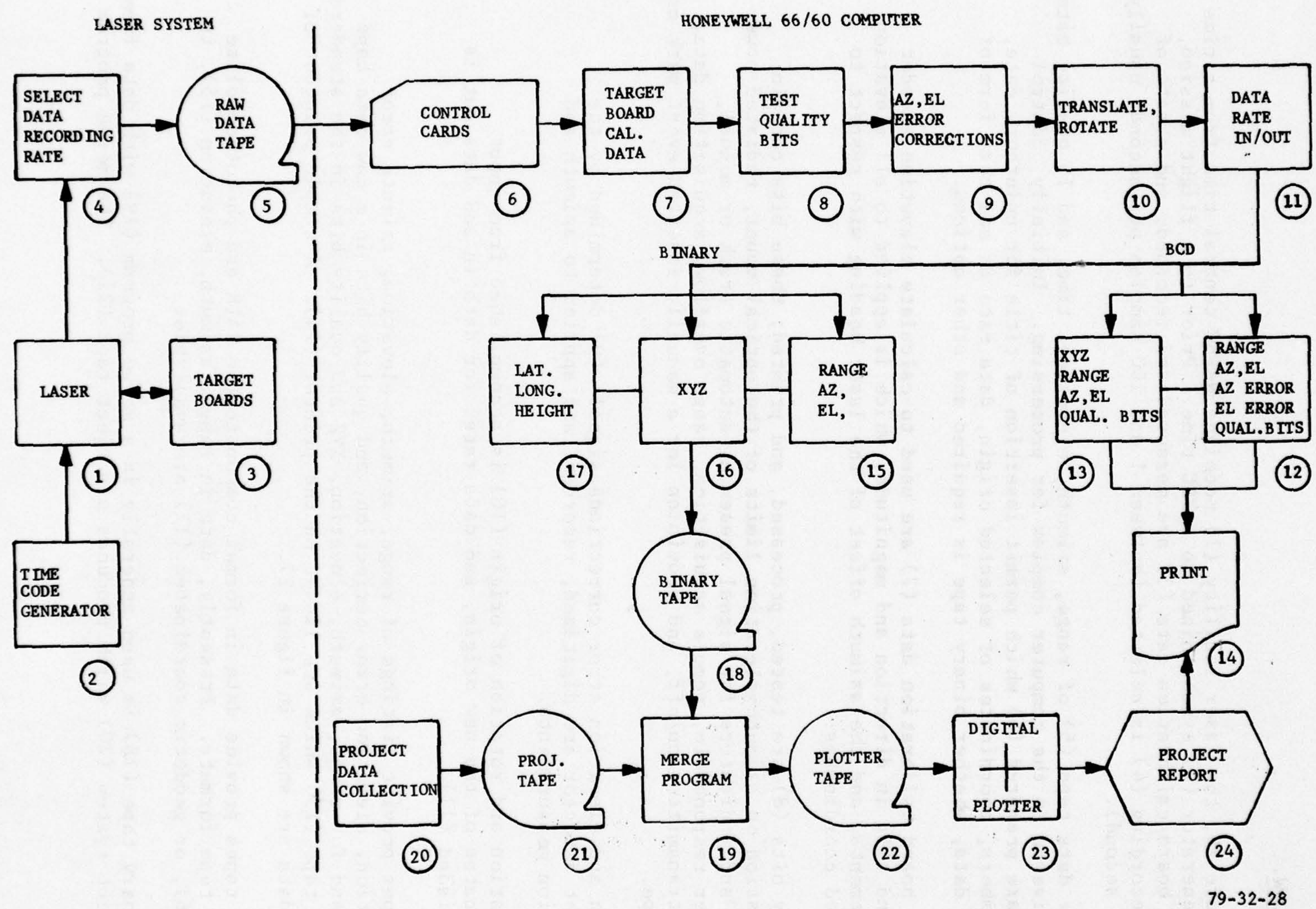

FIGURE 26. LASER SYSTEM DATA FLOW

F A A / N A F E C LASER DATA WITH SPHERICAL AND CARTESIAN COORDINATES A/C NO. 900 FLIGHT NO. 400 RUN NO. 3

DEC. 20, 1978 LASER DATA DATE 12 20 78

TIME HRS	MIN	SEC	X FT.	Y FT.	Z FT.	SLANT RANGE FT.	AZIMUTH ANGLE DEG.	ELEVATION ANGLE DEG.	FLAGS D CLLR A WCCPPOLE RDUCAS NWW1OVOB MVPRTP	EVENT MARK
13	34	39.857	67263.1	-34607.9	2537.2	75686.7	117.227	1.921	000010100010111	20
13	34	39.957	67275.3	-34575.4	2555.6	75683.3	117.200	1.935	000010100010111	20
13	34	40.057	67302.7	-34514.2	2548.4	75679.4	117.150	1.930	000010100010111	20
13	34	40.157	67307.2	-34494.9	2541.4	75674.4	117.135	1.925	000010100010111	20
13	34	40.257	67330.4	-34447.3	2532.6	75673.1	117.095	1.918	000010100010111	20
13	34	40.357	67335.2	-34422.0	2527.2	75665.7	117.076	1.914	000010100010111	20
13	34	40.457	67323.3	-34426.4	2543.9	75657.6	117.083	1.927	000010100010111	20
13	34	40.557	67322.7	-34419.9	2543.7	75654.1	117.079	1.927	000010100010111	20
13	34	40.657	67329.4	-34389.7	2541.6	75646.3	117.057	1.925	000010100010111	20
13	34	40.857	67369.2	-34294.3	2535.8	75638.2	116.978	1.921	000010100010111	20
13	34	40.957	67388.2	-34250.2	2538.9	75635.2	116.942	1.924	000010100010111	20
13	34	41.057	67374.8	-34249.5	2528.3	75622.6	116.946	1.916	000010100010111	20
13	34	41.157	67401.0	-34193.8	2538.2	75621.1	116.900	1.923	000010100010111	20
13	34	41.257	67393.6	-34182.8	2542.8	75609.7	116.895	1.927	000010100010111	20
13	34	41.357	67405.3	-34146.0	2547.5	75603.7	116.866	1.931	000010100010111	20
13	34	41.457	67397.7	-34143.1	2547.3	75595.6	116.866	1.931	000010100010111	20
13	34	41.557	67398.6	-34125.4	2543.5	75588.3	116.854	1.928	000010100010111	20
13	34	41.657	67398.2	-34113.1	2543.3	75582.4	116.846	1.928	000010100010111	20
13	34	41.757	67414.2	-34059.0	2541.0	75572.2	116.804	1.927	000010100010111	20
13	34	41.857	67437.3	-33993.3	2548.9	75563.4	116.751	1.933	000010100010111	20
13	34	41.957	67448.2	-33970.1	2531.8	75562.2	116.732	1.920	000010100010111	20
13	34	42.157	67436.0	-33940.2	2544.4	75538.3	116.716	1.930	000010100010111	20
13	34	42.257	67449.7	-33906.7	2534.0	75535.1	116.689	1.922	000010100010111	20
13	34	42.357	67450.5	-33885.1	2535.3	75526.1	116.674	1.924	000010100010111	20
13	34	42.457	67456.2	-33846.5	2536.4	75514.0	116.645	1.925	000010100010111	20
13	34	42.557	67470.1	-33809.3	2549.6	75510.1	116.615	1.935	000010100010111	20
13	34	42.657	67452.5	-33811.9	2530.5	75495.0	116.623	1.921	000010100010111	20
13	34	42.757	67454.7	-33795.4	2533.6	75489.6	116.611	1.923	000010100010111	20
13	34	42.857	67471.1	-33743.6	2538.2	75481.2	116.571	1.927	000010100010111	20
13	34	42.957	67478.2	-33704.0	2546.1	75470.2	116.541	1.933	000010100010111	20
13	34	43.057	67497.3	-33652.1	2543.9	75464.0	116.499	1.932	000010100010111	20
13	34	43.157	67477.4	-33665.4	2531.8	75451.8	116.515	1.923	000010100010111	20
13	34	43.257	67497.2	-33605.8	2543.0	75443.3	116.468	1.932	000010100010111	20
13	34	43.357	67469.8	-33636.4	2532.7	75432.0	116.498	1.924	000010100010111	20
13	34	43.457	67500.1	-33551.7	2533.6	75421.4	116.430	1.925	000010100010111	20
13	34	43.557	67508.0	-33516.5	2538.2	75413.1	116.404	1.929	000010100010111	20
13	34	43.657	67498.2	-33508.4	2527.6	75400.3	116.401	1.921	000010100010111	20
13	34	43.757	67500.9	-33476.1	2528.8	75388.5	116.378	1.922	000010100010111	20
13	34	43.857	67488.8	-33468.5	2538.4	75374.5	116.377	1.930	000010100010111	20
13	34	43.957	67516.0	-33401.9	2529.5	75369.1	116.323	1.923	000010100010111	20
13	34	44.057	67516.5	-33372.2	2542.4	75356.8	116.302	1.933	000010100010111	20
13	34	44.157	67503.4	-33366.0	2525.0	75341.8	116.303	1.921	000010100010111	20
13	34	44.257	67527.5	-33303.4	2527.9	75335.8	116.252	1.923	000010100010111	20
13	34	44.357	67531.1	-33275.6	2524.1	75326.5	116.232	1.920	000010100010111	20
13	34	44.457	67509.2	-33279.8	2530.3	75309.0	116.242	1.925	000010100010111	20
13	34	44.557	67505.5	-33261.6	2526.4	75297.5	116.231	1.923	000010100010111	20
13	34	44.657	67513.4	-33214.7	2537.5	75284.2	116.196	1.932	000010100010111	20
13	34	44.757	67528.6	-33162.6	2533.6	75274.8	116.155	1.929	000010100010111	20
13	34	44.857	67527.9	-33136.1	2528.0	75262.2	116.137	1.925	000010100010111	20
13	34	45.057	67510.6	-33105.5	2523.5	75233.2	116.122	1.922	000010100010111	20

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FIGURE 27. SAMPLE LASER DATA LISTING

commonly provides for plots of comparative data (23) upon which reports (24) are based.

SYSTEM ACCURACY.

A flight test on November 15, 1978, with laser and EAIR, acquired data that was used in a report, "Statistical Analysis Support for Airborne Separation Assurance Support Systems" (Contract DOT-FA74-NA-1027, Task 13). The data were evaluated for a statistical estimate of the standard deviation of laser errors in azimuth, elevation, and range. The estimates of error obtained were:

Azimuth: 0.0086°
Elevation: 0.0128°
Range: 2.6 feet (at 6 nmi).

Several reflectors are in use at NAFEC to provide calibration of the laser. These target board data are measured and recorded prior to and immediately following each flight test period.

Elevation data from the target board measurements are processed in the computer program for comparison with the survey values, thereby establishing tilt error which is used by the program to compute and apply corrections to target elevation data.

Range bias as determined from the comparison of measured and survey values permit adjustment, if necessary, of range bias at the facility. Additionally, there is a propogation correction to range measurements that can be made at the facility in which range is corrected proportional to distance of the target.

Analysis of target board data for several periods yields standard deviation of:

Azimuth: 0.0070°
Elevation: 0.0135°, (the 0.011° elevation error bit was later found to be not functioning at the time. Corrected target board data with the 0.011° bit included was found to provide an error figure of 0.0013° elevation) and the system specification of standard deviation in range is given as:

1 - 5 nmi: 1 feet
5 -10 nmi: 2 feet
10-25 nmi: 5 feet

These figures suggest excellent correlation between static target board data and dynamic tracking data, and support the contention that target board data prior to and following flight test periods have a high probability of being representative of tracking data from that flight.

Laser specifications are given in table 6.

TABLE 6. LASER SPECIFICATIONS

LEADING PARTICULAR	CHARACTERISTIC
COVERAGE	
Azimuth:	540°
Elevation:	-5° to +105° (dynamic specifications apply for -5° to elevation)
Range:	25 nautical miles through touchdown and rollout (dependent on visibility conditions)
SYSTEM ACCURACY	
Azimuth:	±20 arc seconds at all ranges including touchdown and rollout
Elevation:	±20 arc seconds at all ranges including touchdown and rollout
Range:	±1 foot for target ranges out to 5 nmi ±2 foot for target ranges 5 to 10 nmi ±5 foot for target ranges at 25 nmi
MAXIMUM ANGULAR RATE IN AUTOMATIC MODE	
Azimuth:	500 mrad/seconds
Elevation:	50 mrad/seconds
MAXIMUM ANGULAR ACCELERATION IN AUTOMATIC MODE	
Azimuth:	80 $mrad/sec^2$
Elevation:	80 $mrad/sec^2$
DATA SAMPLE RATE	
100, 50, 20, 10 samples per second (switch selectable)	
DATA ENCODERS	
Azimuth:	18 bits
Elevation:	18 bits
Range:	18 bits
*Az Error:	8 bits
*El Error:	8 bits
ENVIRONMENTAL CONDITIONS (OPERATING)	
Ambient temperature 0° F to 110° F	
Relative humidity 0 to 100%	
Wind 0 to 50 knots	

*These are derived from a detector, which provides voltage analogs of azimuth and elevation tracking errors on the target return. These error signals are digitized.

SAFETY.

Operational safety of the laser tracker involves several precautions. To assure personnel safety during operation, the laser and personnel are housed in a steel, windowless trailer. Goggles are required outside the trailer unless the laser power supply is turned off. When the power supply is off, a steel shutter automatically swings in front of the laser exit port.

The laser is equipped with a computer-controlled eyesafe system that switches mechanical attenuators into the laser output beam to keep the laser transmitted power at the target to an eyesafe level. In addition, there is a fail-safe circuit that shuts down the laser in case of attenuator or computer program failure.

NIKE/HERCULES RADARS

The original Nike/Hercules system was designed to track targets and to launch and track missiles using highly accurate radars. The system contained two X-band radars, one designated a target tracking radar (TTR) and one designated a missile tracking radar (MTR) (figure 28). These acronyms, TTR and MTR, are continued in use with the converted system.

In its original function, all data in the Nike/Hercules system were processed in analog form, including the use of an analog guidance computer. The basic radar, however, was highly functional. In particular, the pedestals provided the excellent precision for pin-point tracking that deemed the system an excellent candidate for conversion to a modern digital instrumentation radar system.

MODIFICATIONS.

Modification work performed on the NAFEC-acquired Nike/Hercules system consisted mainly of converting range, azimuth, and elevation data to digital form for recording and display, and the introduction of microprocessors to process data and to perform the interface operations between radar and operator.

In addition, a second van was added to the system--a computer van that houses the data handling system which includes a General Automation digital computer and various peripheral devices to process, display, and record radar data.

The MTR/TTR radar van is shown in figure 28. The precision radar pedestal is shown in figure 29. A diagram of the modified system configuration is shown in figure 30.

Each radar, MTR and TTR, has television camera coverage from their respective pedestals. Television monitoring provides target acquisition aid and is useful in monitoring target progress when the aircraft is within visual range.

Each pedestal contains its respective magnetron transmitter and RF section of its receiver. In addition, the pedestals also house the modification equipment that include the angle encoders for azimuth and elevation data, and a tilt meter that is used to provide calibration data on pedestal elevation leveling. New, coaxial magnetrons were installed with each radar.

Within the radar van are located the radar set group, the missile radar control console (figure 31), and the target radar control console (figure 32).

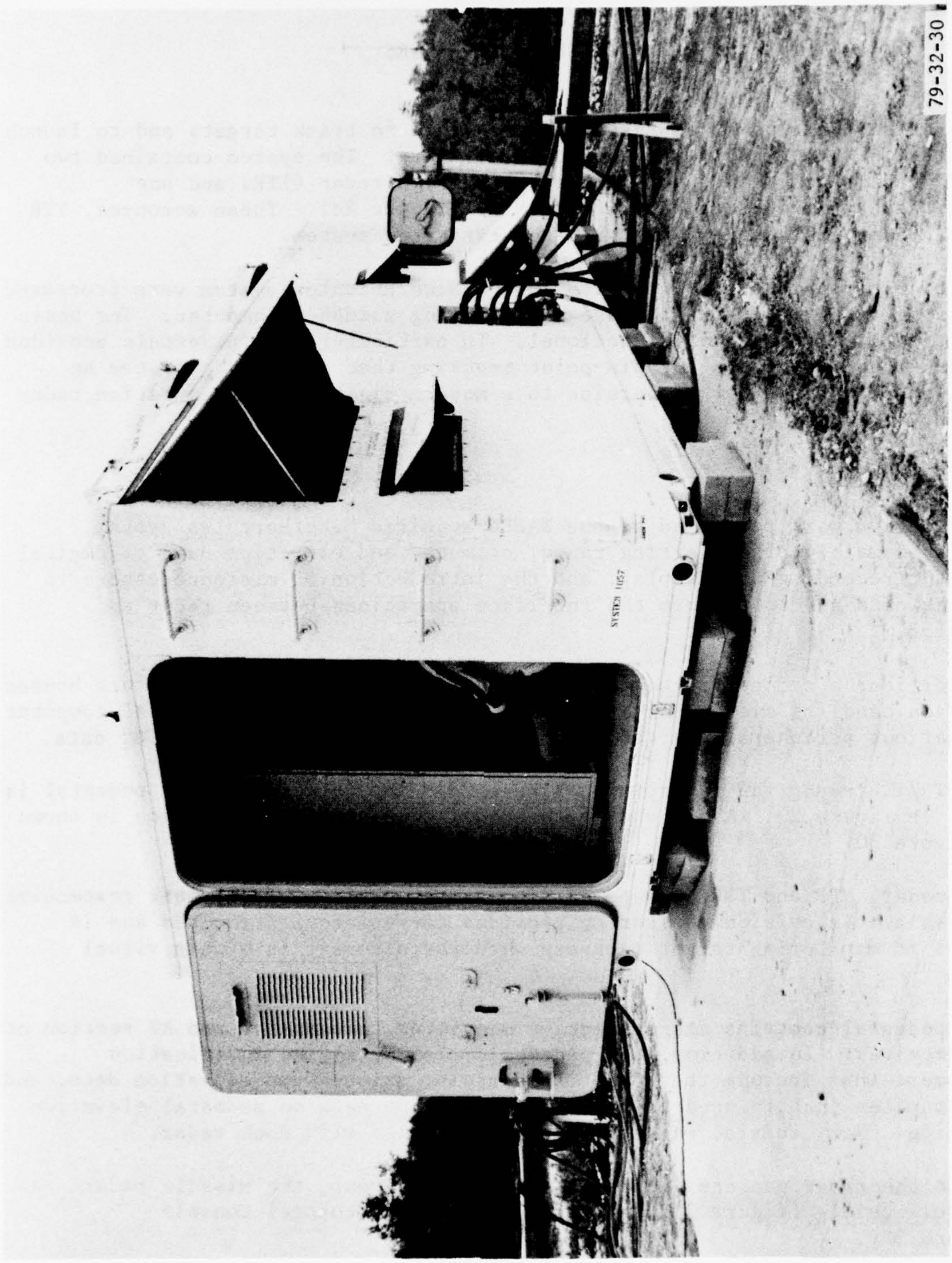

FIGURE 28. NIKE/HERCULES RADAR VAN

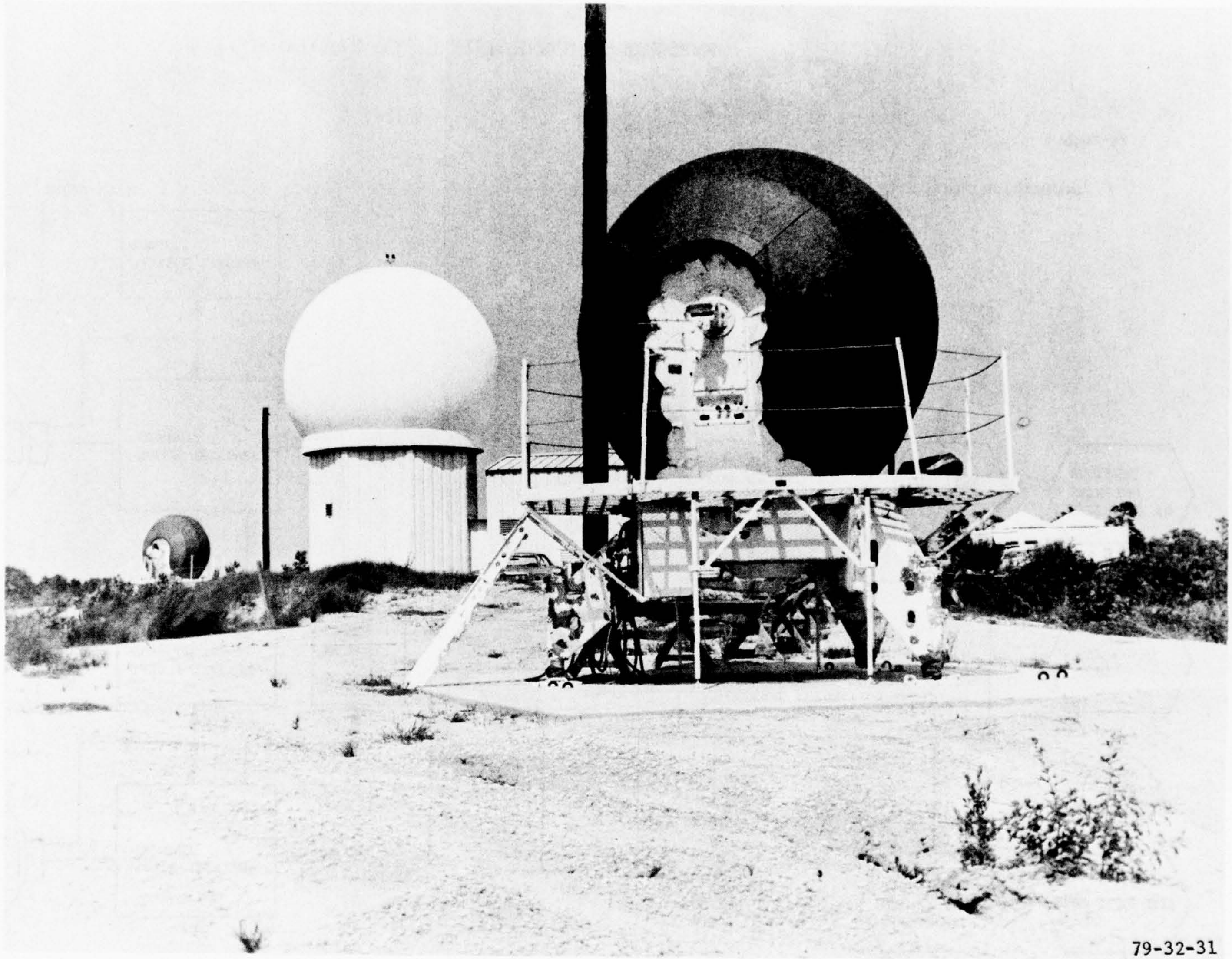

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FIGURE 29. NAFEC RADAR RANGE

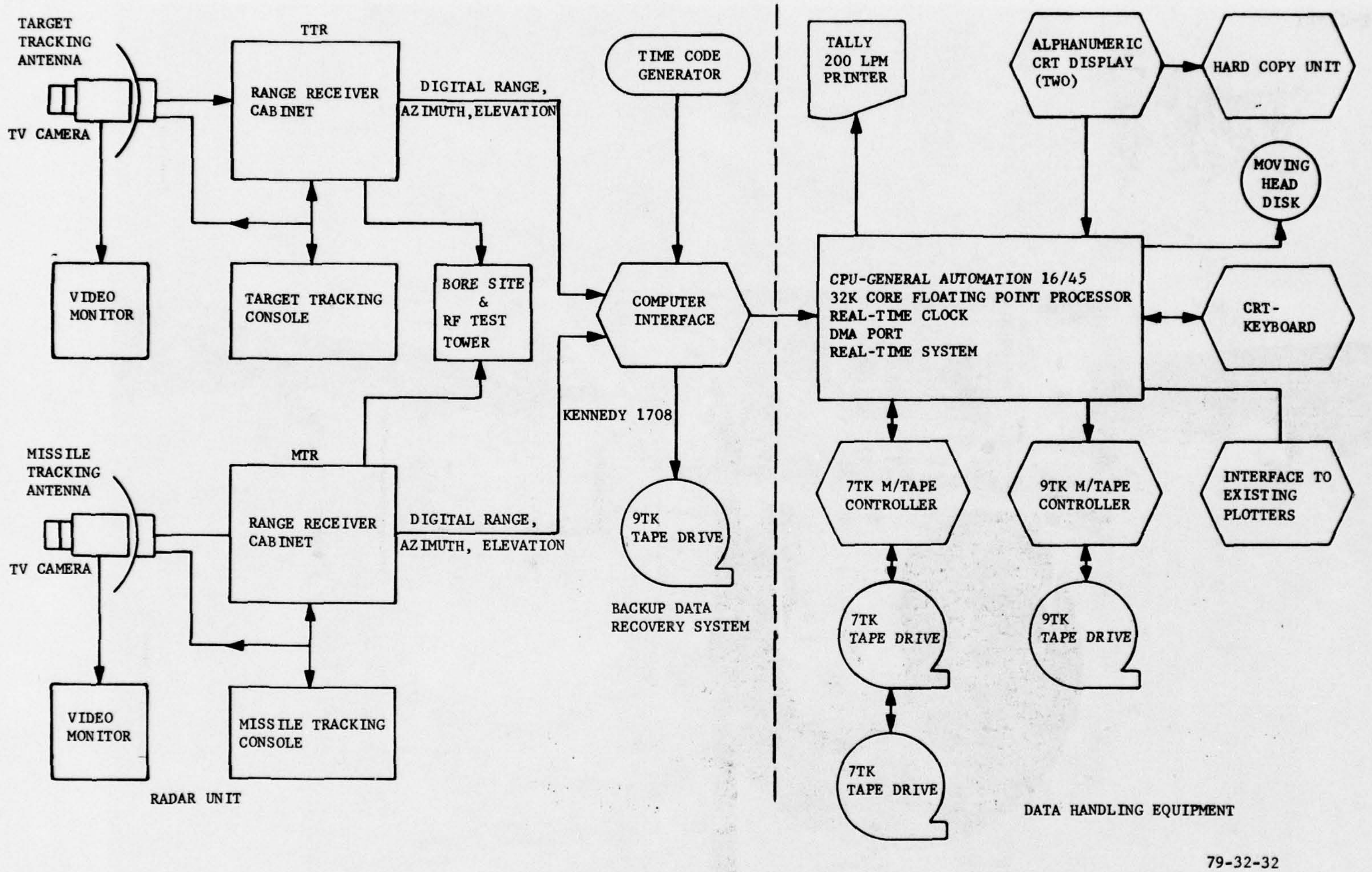

FIGURE 30. NIKE/HERCULES DIAGRAM

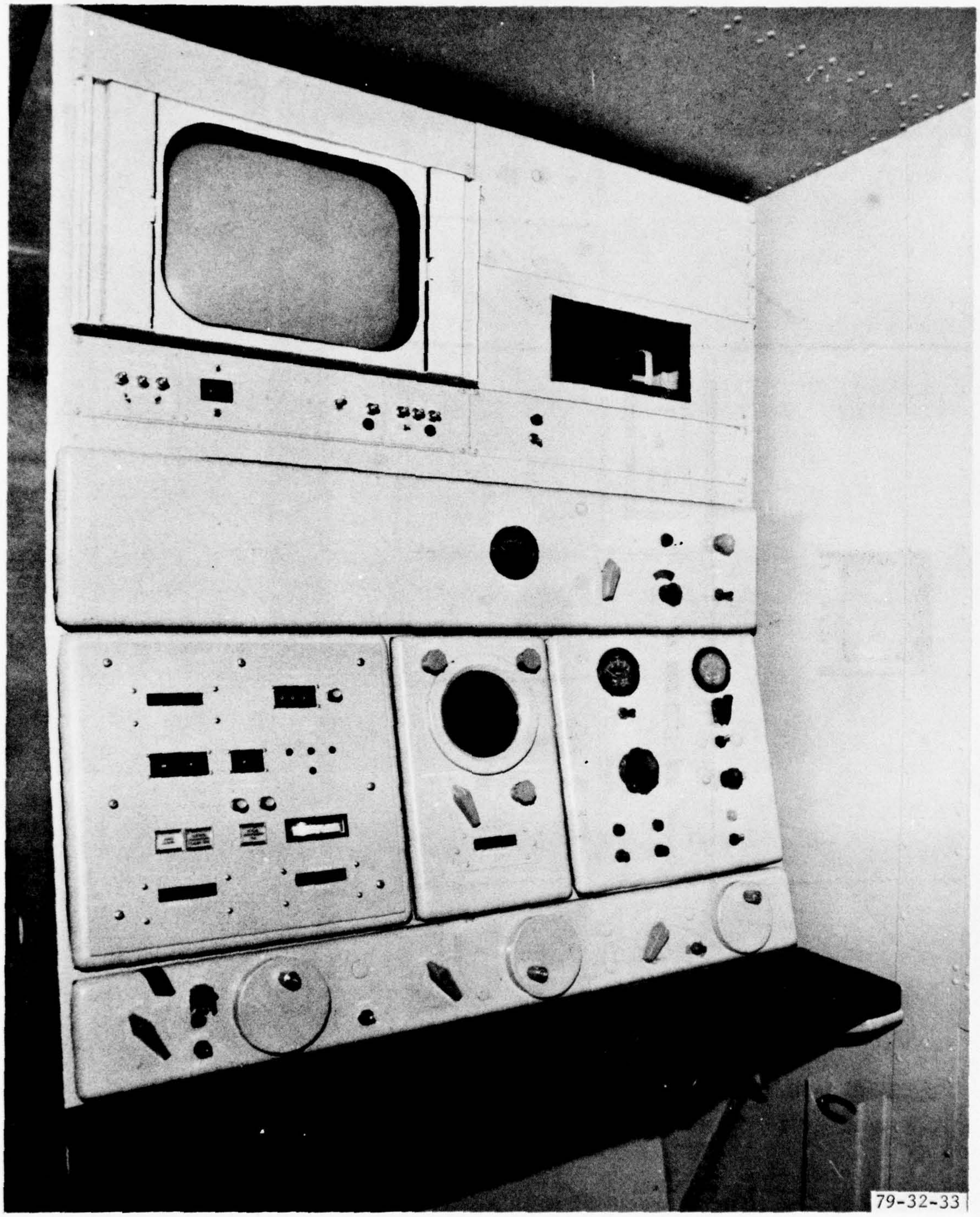

FIGURE 31. MTR CONSOLE

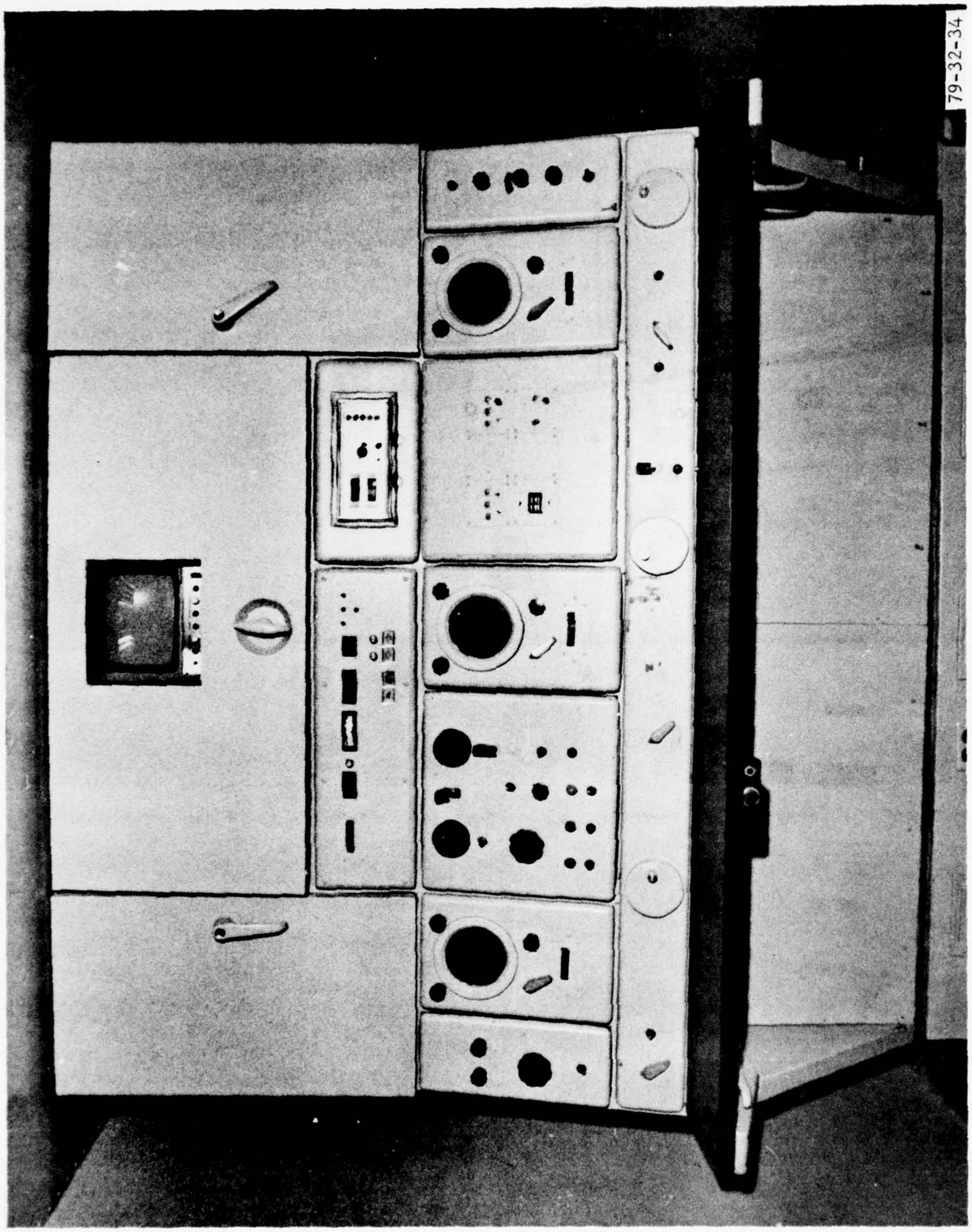

FIGURE 32. TTR CONSOLE

Digitized range, azimuth, and elevation data from either or both radars are processed through the computer interface, which also receives time-of-day signals from an added time code-generator.

A nine-track tape drive in the radar van records raw data as a backup source, should any malfunction occur in processing or recording data in the computer van.

COMPUTER VAN.

The data handling equipment within the computer van (photos, figures 33, 34, and 35) contains a digital computer which interconnects with the radar trackers. The data handling equipment receives target data from either or both radars, records these data, performs specific functions with the data, (such as filtering, velocity calculations, and target track), records selected processed data, and prepares data for output to graphics, plotter displays, or magnetic tape drives.

Hardware components of the computer van include:

- General automation SPC 16/65 digital computer
- floating point processor
- two nine-track tape drives
- one seven-track tape drive
- Hazeltine alphanumeric CRT and keyboard
- two Hughes graphic CRT displays and keyboards
- two Calcomp Model 563 plotters
- card reader
- line printer, 200 LPM
- paper tape reader/punch
- four digital/analog converters

The Hazeltine keyboard is used to interact with the computer. Two Hughes terminals direct processing of data from the respective radar, MTR or TTR.

Software allows the operator to dynamically interface with the system real-time.

TEST TOWER.

A radiofrequency (RF) test tower (figure 36) located approximately 600 feet from the radar antennas, is used to provide signal sources for adjusting each radar's transmitting and receiving frequencies, and to establish receiver sensitivities.

The tower position is surveyed with repect to the radars, as is the feed horn on top of the tower. Target boards extending either side of the feed horn

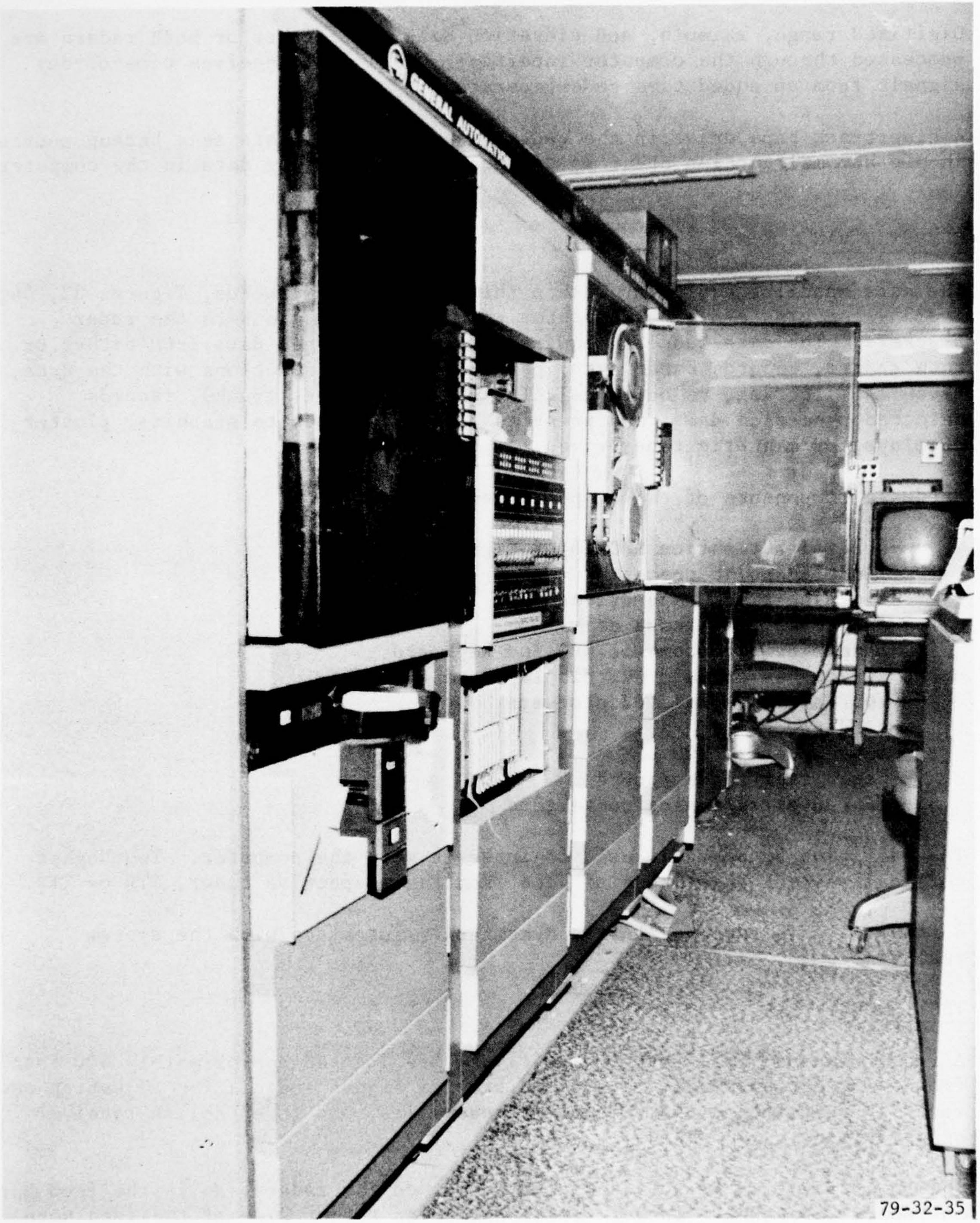

FIGURE 33. GA COMPUTER

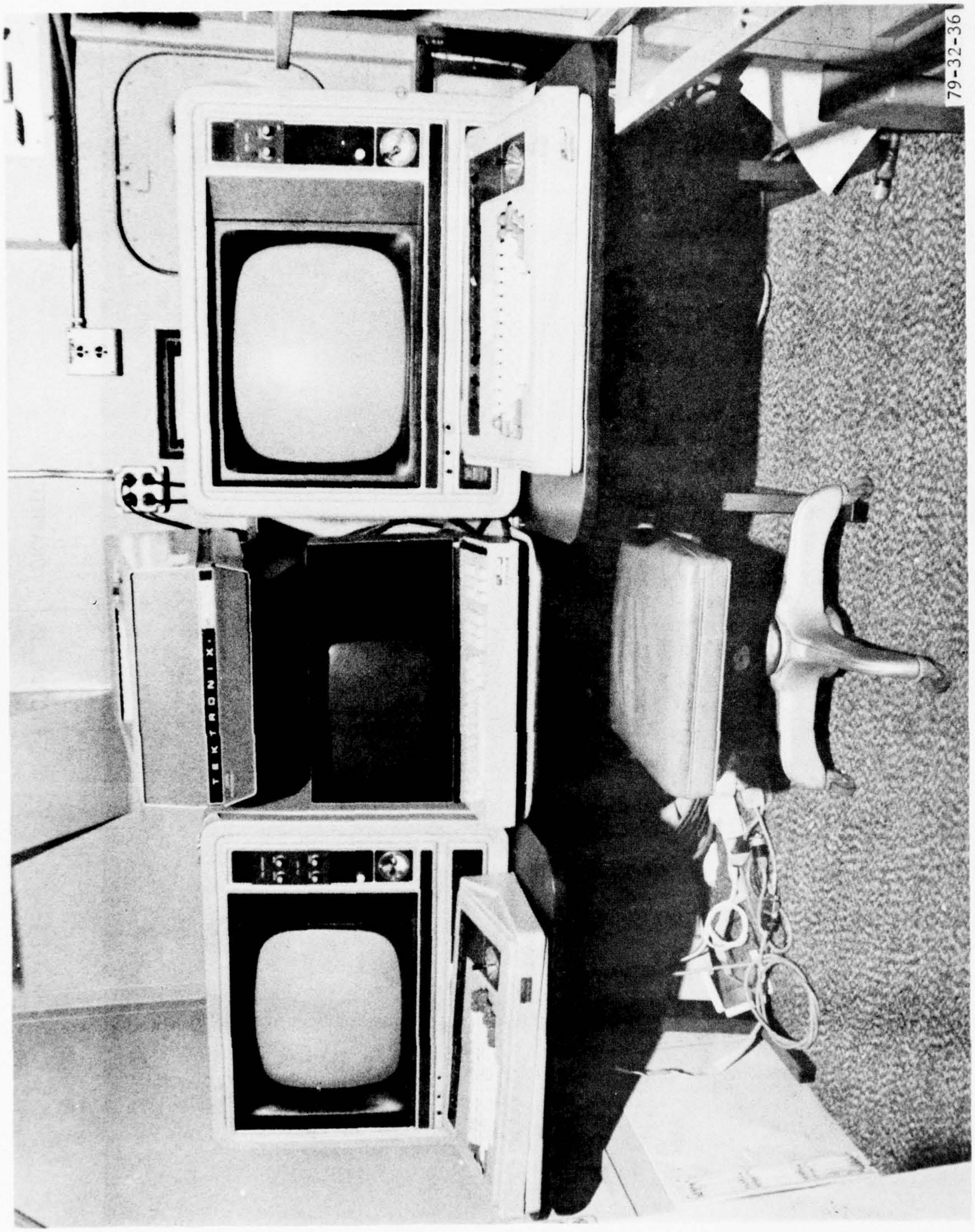

FIGURE 34. TERMINALS

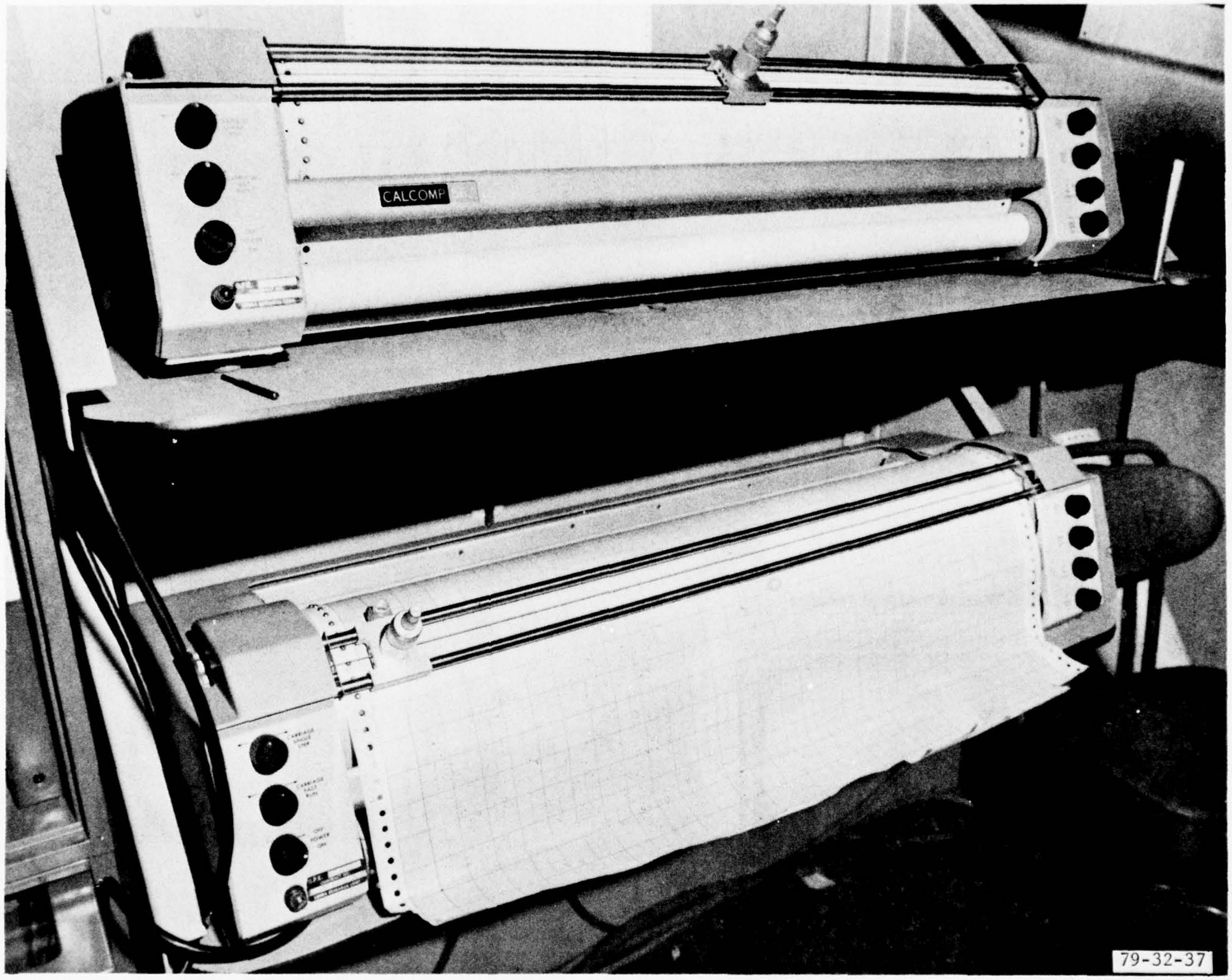

FIGURE 35. GRAPHICS

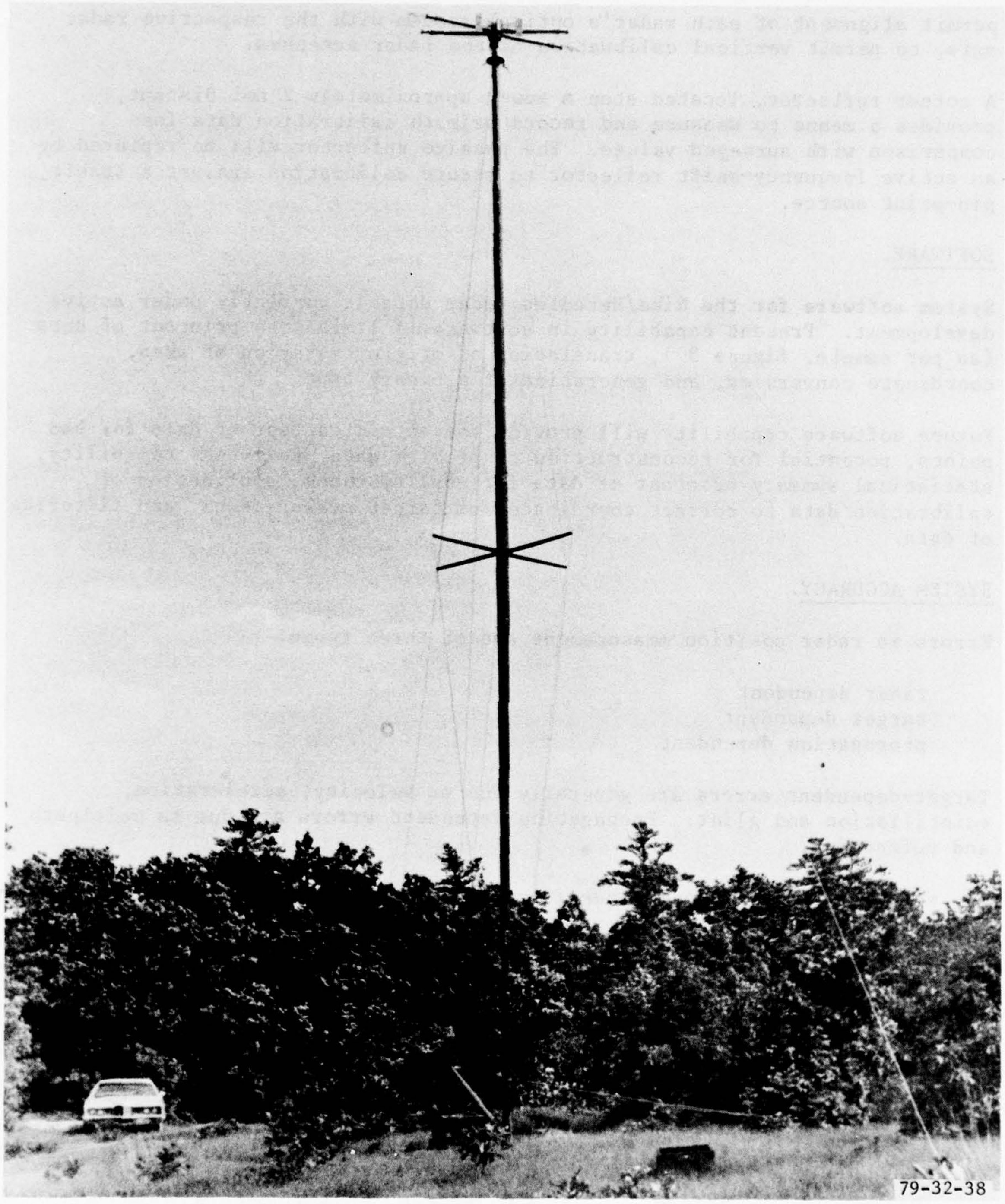

FIGURE 36. RF TEST TOWER

permit alignment of each radar's optical system with the respective radar axis, to permit vertical calibration of the radar antennas.

A corner reflector, located atop a tower approximately 2 nmi distant, provides a means to measure and record azimuth calibration data for comparison with surveyed values. The passive reflector will be replaced by an active frequency-shift reflector to assure calibration against a stable, pin-point source.

SOFTWARE.

System software for the Nike/Hercules radar data is currently under active development. Present capability in software is limited to printout of data (as per sample, figure 37), translation of origin, rotation of axes, coordinate conversion, and generation of a binary tape.

Future software capability will provide for automated test of data for bad points, potential for reconstruction of problem data, self-test capability, statistical summary printout of data for quality check, application of calibration data to correct coordinates of target measurements, and filtering of data.

SYSTEM ACCURACY.

Errors in radar position measurement are of three types:

- radar dependent
- target dependent
- propogation dependent

Target-dependent errors are generally due to velocity, acceleration, scintillation and glint. Propagation dependent errors are due to multipath and refraction.

The theoretical error budget considers only those errors attributable to the radar itself.

The theoretical error budget for the MTR and TTR is as follows:

		MTR	TTR
Azimuth	Random	0.15 mrad	0.15 mrad
	Bias	0.25 mrad	0.25 mrad
Elevation	Random	0.15 mrad	0.15 mrad
	Bias	0.25 mrad	0.25 mrad
Range	Random	3.0 meters	3.0 meters
	Bias	6.0 meters	6.0 meters

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TIME	TRACK	VALID	AGC	MTR AZ	EL	RANGE	TRACK	VALID	AGC	TTR AZ	EL	RANGE
11 36 34.9	A	T	4.16	-13.60	8.47	130664.78	A	T	7.64	-13.59	8.46	130684.34
11 36 35.0	A	T	4.16	-13.58	8.46	130697.54	A	T	7.64	-13.57	8.46	130713.54
11 36 35.1	A	T	4.17	-13.57	8.46	130723.70	A	T	7.65	-13.56	8.46	130743.15
11 36 35.2	A	T	4.15	-13.55	8.46	130753.60	A	T	7.65	-13.54	8.46	130772.51
11 36 35.3	A	T	4.15	-13.53	8.46	130786.16	A	T	7.66	-13.52	8.46	130802.02
11 36 35.4	A	T	4.14	-13.52	8.46	130815.79	A	T	7.65	-13.51	8.45	130834.82
11 36 35.5	A	T	4.14	-13.50	8.46	130845.35	A	T	7.65	-13.49	8.45	130864.31
11 36 35.6	A	T	4.14	-13.48	8.45	130875.03	A	T	7.64	-13.48	8.45	130893.87
11 36 35.7	A	T	4.13	-13.47	8.45	130904.35	A	T	7.62	-13.46	8.45	130923.10
11 36 35.8	A	T	4.12	-13.45	8.45	130933.97	A	T	7.61	-13.44	8.45	130952.83
11 36 35.9	A	T	4.12	-13.44	8.45	130963.43	A	T	7.61	-13.43	8.44	130985.53
11 36 36.0	A	T	4.11	-13.42	8.45	130996.43	A	T	7.60	-13.41	8.44	131014.99
11 36 36.1	A	T	4.09	-13.40	8.44	131025.87	A	T	7.59	-13.39	8.44	131044.96
11 36 36.2	A	T	4.09	-13.39	8.44	131058.85	A	T	7.58	-13.38	8.44	131073.88
11 36 36.3	A	T	4.06	-13.37	8.44	131088.24	A	T	7.56	-13.36	8.43	131106.81
11 36 36.4	A	T	4.04	-13.35	8.44	131117.80	A	T	7.54	-13.34	8.43	131136.09
11 36 36.5	A	T	4.02	-13.34	8.43	131150.85	A	T	7.52	-13.33	8.42	131165.45
11 36 36.6	A	T	4.00	-13.32	8.43	131180.05	A	T	7.51	-13.31	8.42	131195.02
11 36 36.7	A	T	3.99	-13.31	8.43	131209.45	A	T	7.50	-13.30	8.42	131227.96
11 36 36.8	A	T	3.96	-13.29	8.43	131242.34	A	T	7.48	-13.28	8.41	131257.32
11 36 36.9	A	T	3.96	-13.27	8.43	131272.17	A	T	7.46	-13.27	8.41	131286.78
11 36 37.0	A	T	3.94	-13.26	8.42	131301.62	A	T	7.46	-13.25	8.41	131316.29
11 36 37.1	A	T	3.93	-13.24	8.42	131331.22	A	T	7.47	-13.23	8.40	131345.81
11 36 37.2	A	T	3.92	-13.23	8.42	131360.54	A	T	7.46	-13.22	8.40	131375.27
11 36 37.3	A	T	3.93	-13.21	8.42	131389.96	A	T	7.48	-13.20	8.40	131408.00
11 36 37.4	A	T	3.92	-13.19	8.42	131419.78	A	T	7.48	-13.19	8.40	131434.19
11 36 37.5	A	T	3.91	-13.18	8.42	131452.40	A	T	7.48	-13.17	8.40	131466.92
11 36 37.6	A	T	3.91	-13.16	8.41	131478.71	A	T	7.50	-13.15	8.39	131496.60
11 36 37.7	A	T	3.91	-13.15	8.41	131511.75	A	T	7.53	-13.14	8.39	131529.20
11 36 37.8	A	T	3.90	-13.13	8.41	131544.46	A	T	7.54	-13.12	8.39	131558.91
11 36 37.9	A	T	3.90	-13.11	8.41	131573.93	A	T	7.54	-13.10	8.39	131588.04
11 36 38.0	A	T	3.90	-13.10	8.41	131603.32	A	T	7.55	-13.09	8.39	131617.68
11 36 38.1	A	T	3.91	-13.08	8.40	131633.23	A	T	7.54	-13.07	8.39	131647.17
11 36 38.2	A	T	3.91	-13.06	8.40	131662.73	A	T	7.55	-13.05	8.38	131679.68
11 36 38.3	A	T	3.91	-13.05	8.40	131692.25	A	T	7.55	-13.04	8.38	131709.27
11 36 38.4	A	T	3.92	-13.03	8.40	131725.03	A	T	7.56	-13.02	8.38	131738.99
11 36 38.5	A	T	3.94	-13.01	8.40	131758.02	A	T	7.57	-13.01	8.38	131768.54
11 36 38.6	A	T	3.95	-13.00	8.40	131787.16	A	T	7.57	-12.99	8.38	131801.04
11 36 38.7	A	T	3.96	-12.98	8.39	131817.16	A	T	7.57	-12.98	8.37	131833.80
11 36 38.8	A	T	3.95	-12.97	8.39	131846.76	A	T	7.57	-12.96	8.37	131863.42
11 36 38.9	A	T	3.96	-12.95	8.39	131876.22	A	T	7.57	-12.95	8.37	131892.86
11 36 39.0	A	T	3.98	-12.94	8.39	131908.78	A	T	7.57	-12.93	8.37	131922.04
11 36 39.1	A	T	3.97	-12.92	8.38	131935.29	A	T	7.59	-12.91	8.37	131954.86
11 36 39.2	A	T	3.99	-12.90	8.38	131967.74	A	T	7.61	-12.90	8.37	131984.54
11 36 39.3	A	T	3.98	-12.89	8.38	131997.43	A	T	7.62	-12.88	8.36	132014.12
11 36 39.4	A	T	3.99	-12.87	8.38	132030.35	A	T	7.62	-12.87	8.36	132043.37
11 36 39.5	A	T	4.01	-12.86	8.38	132056.50	A	T	7.61	-12.85	8.36	132073.02
11 36 39.6	A	T	4.02	-12.84	8.38	132089.47	A	T	7.61	-12.84	8.36	132105.69
11 36 39.7	A	T	4.04	-12.82	8.37	132122.06	A	T	7.61	-12.82	8.36	132135.16
11 36 39.8	A	T	4.05	-12.81	8.37	132151.86	A	T	7.61	-12.81	8.36	132164.58

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FIGURE 37. SAMPLE NIKE/HERCULES DATA LISTING

The term bias error means the residue of systematic errors after all corrections have been applied to the measurement.

The range bias was determined from differences in tracker-computed range and known survey range when fully locked on to a beacon installed at a known survey point. The random range error was measured at the known survey point and, in all cases, was less than the theoretical value (6.0 meters, 1 sigma).

The elevation angle bias was determined from the difference in optical measurements of elevation angle and known elevation of the Nike-Hercules Radar System RF Test Stand. The random elevation error was measured at the RF Test Stand and in all cases was less than the theoretical value (0.15 milliradians (mrad), 1 sigma).

The azimuth angle bias was determined from differences between optical measurements of azimuth angle and the known azimuth of a well defined reflective target (the Atlantic City Racetrack Tower). The random azimuth error was measured at the RF Test Stand and in all cases was less than the specified value (0.15 mrad, 1 sigma).

The elevation and azimuth bias angles determined above were verified by sighting on several selected stars and converting the error in time of predicted passage to angular bias errors. In all sighting cases the resultant error was less than the theoretical bias error (0.25 mrad, 1 sigma) for both the MTR and TTR.

The reduction of measurements to fall within these error bounds is dependent on the following:

1. Correction for RF bias in azimuth and elevation antennas
2. Correction for platform tilt
3. Correction for refraction
4. Correction for beacon delay and length of transmission line used between beacon and antenna.

Actual flight data collected on June 18, 1979, were reduced to obtain the following summary statistics for differences between MTR and TTR measurements. Both radars were tracking the same aircraft. About 15 minutes of data were selected from two flight patterns, providing:

490 differences from a radial pattern of 12 to 13.4 nmi range at 90° azimuth and 5,000 feet altitude, and

8,630 differences from a 6-nmi orbital pattern at 5,000 feet altitude.

Standard Deviation	Azimuth (mrad)	Elevation (mrad)	Range (meters)
(MTR-TTR) all data	0.134	0.134	3.25
MTR or TTR	0.10	0.10	3.0 MTR
Predicted	0.15	0.15	3.0
Mean			
(MTR-TTR) radial	0.08	-0.34	1.3
(MTR-TTR) orbit	0.11	-0.36	4.9
MTR or TTR		(indeterminate)	
Predicted Bias	0.25	0.25	6.0

The standard deviation of random azimuth or elevation errors is 0.10 mrad for the MTR or TTR, which is that given in the Nike/Hercules specifications. The theoretical error budget for radar dependent errors only is 0.15 mrad.

The standard deviation of random range errors is 3.0 meters for the MTR and 1.1 meters for the TTR based on a ratio of about 3 to 1 established from RF tower measurements. The theoretical error budget is 3.0 meters.

Mean errors in azimuth, elevation, and range for the MTR or TTR are indeterminate; they cannot be estimated from MTR-TTR differences alone. The irreducible bias for either radar is 0.25 mrad in angle and 6.0 meters in range.

Reduction of the above flight data did not include corrections for RF bias in azimuth and elevation antennas for platform tilt.

Nike/Hercules specifications are given in table 7.

TABLE 7. NIKE/HERCULES SPECIFICATIONS

LEADING PARTICULAR	CHARACTERISTIC
Antenna	Vertical, linear
Reflector	Cassegrainian parabolic reflector, pencil pattern, diameter 7' 9".
Azimuth Limits of Operation	360° continuous
Elevation Limits of Operation	-5° to 90°, continuous
Gain	42 dB
Beamwidth	1.1°
Side Lobes	17 dB down
Null Depth	30 dB down
Leveling	Precision orthoganal
Transmitter	Tunable magnetron
Frequency Range	8.5 GHz to 9.6 GHz
Peak Power	250 kW
Pulse Coding	Two pulses, adjustable spacing from 0.5 ms to 5.09 ms
PRF	320 or 1,000 pps, selectable
Pulse Duration	0.25 μs
Range Limits	200 nmi
Range Precision	1 meter
Angle Precision	0.0057°
Receiver	
Noise Figure	8.5 dB
Dynamic Range	110 dB
Bandwidth	10 MHz
Intermediate Frequency (IF)	60 MHz
Modes of Operation	Manual, aided, automatic
Maximum Tracking Rates	
Range	
Aided	2,000 meters/second
Auto	2,600 meters/second
Slew	18,000 meters/second
Angle	
Aided	420 mils/second
Auto/Slew	700 mils/second
Digital Data	
Range	18 bits
Least Significant Bit	1 meter
Angle	18 bits
Least Significant Bit	0.0014°
Range Tracker	Type II Serve loop, leading edge/ centroid tracking, selectable.

AIR-TO-AIR RANGING AND BEARING SYSTEM

The NAFEC air-to-air ranging and bearing system shown in figure 38 uses digital TACAN navigational sets (models AN/ARN-84(V)) to measure slant range to cooperating aircraft. Air-to-air bearing is also available when one of the aircraft contains a special airborne rotating TACAN antenna.

SYSTEM DESCRIPTION.

Air-to-ground TACAN is an air navigational system that provides aircraft with continuous ranging and bearing information to or from a ground station. It has 252 two-way operating channels in the portion of the spectrum between 962 MHz and 1213 MHz, and each channel uses two sperate frequencies 63 MHz apart for their transmit/receive functions.

In air-to-air TACAN, ranging between two aircraft is made possible by the addition of a transponding function to the airborne equipment, and by a transposition of paired frequencies per channel so that neither aircraft in the air-air link communicate with any ground station, but only with each other. Both ends of the air-air link can display range information.

Air-to-air bearing is made possible primarily through installation of a special airborne TACAN rotating antenna, such as the mechanical scan type in use at NAFEC and as shown in figure 38. State-of-the-art development of airborne rotating antennas is now primarily aimed at development of electronic scan capability.

Three AN/ARN-84(V) TACAN sets are in use at NAFEC, two in digital racks as shown in the photograph, and one in what is commonly referred to as the "analog" rack; that is, it does not contain a formatter or recorder. It is to provide a cooperative signal for either digital rack.

OPERATION.

A block diagram of the digital system is shown in figure 39.

The AN/ARN-84(V) navigational set is a combination transmitter, receiver, decoder, digital computer, and digital-to-analog converter that can perform the normal air-ground functions as well as provide the necessary features for use in the air-to-air mode.

Functions of the TACAN sets are controlled from the control head to permit selection of channel (up to 126), operating mode (receive, transmit/receive, air-air, and beacon), bearing mode selection (normal/inverse), X or Y submode selection, and built-in test.

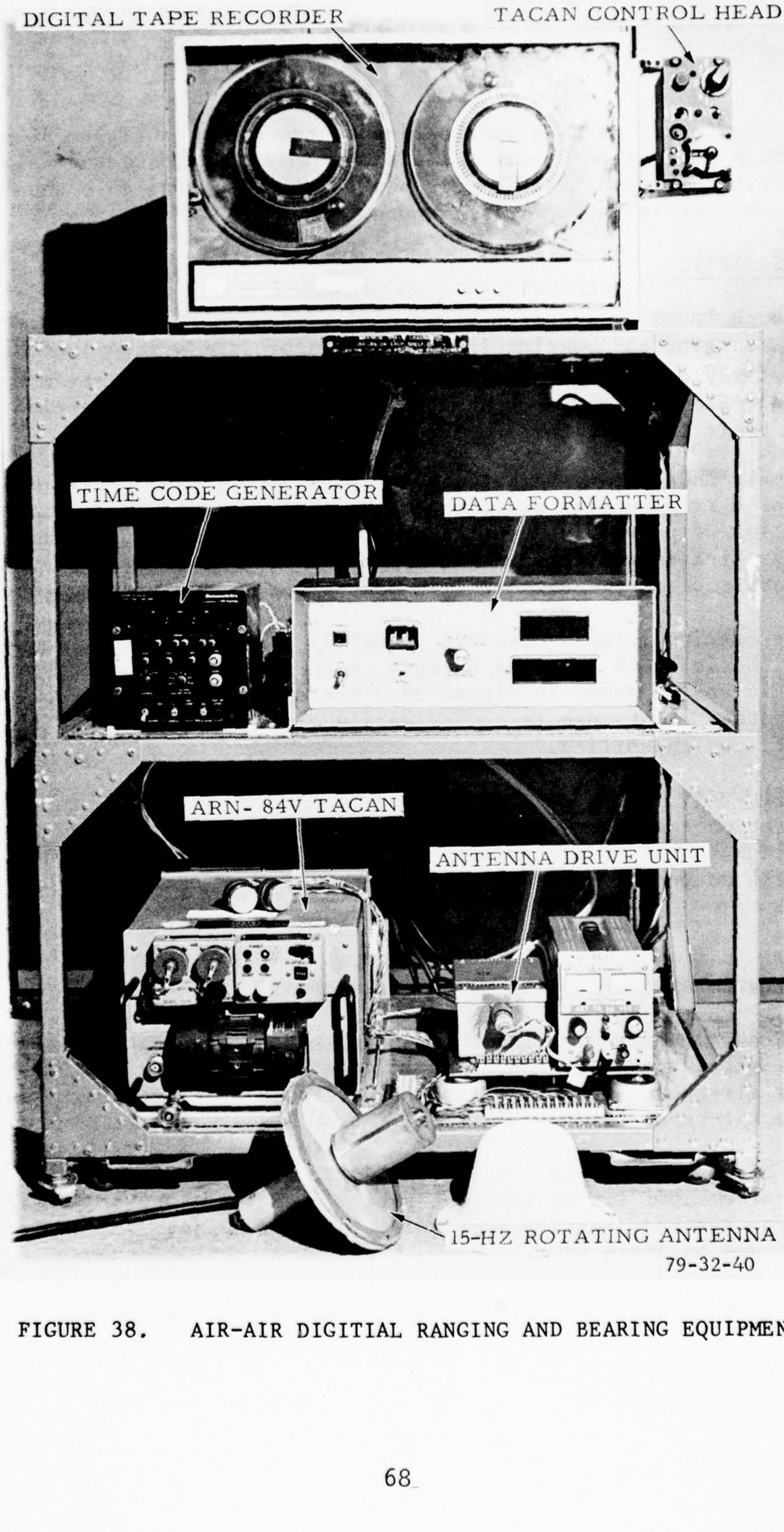

FIGURE 38. AIR-AIR DIGITIAL RANGING AND BEARING EQUIPMENT

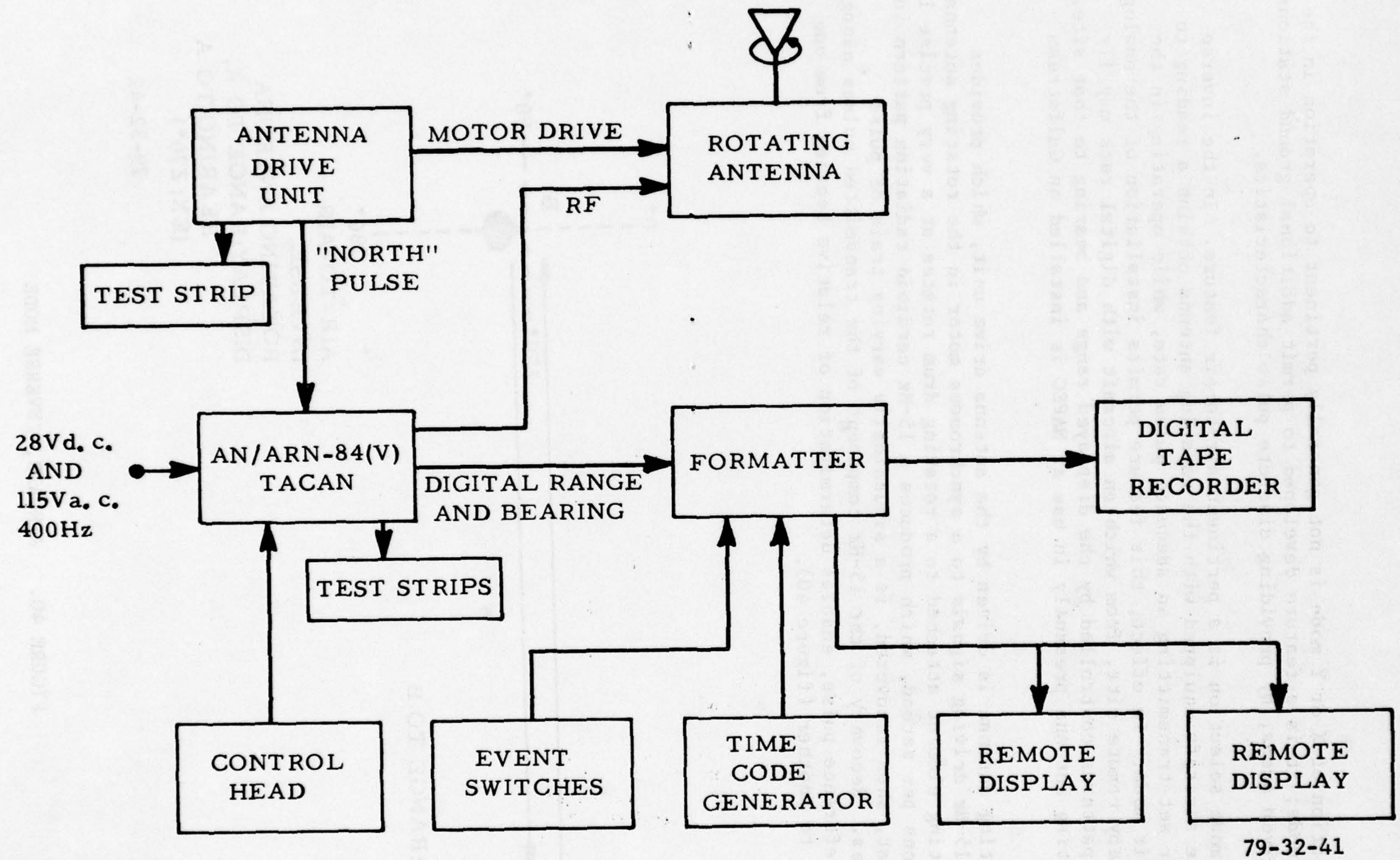

FIGURE 39. DIGITAL SYSTEM BLOCK DIAGRAM

The selection of X or Y mode is not generally pertinent to operation in the air-air mode; it is a feature developed to permit additional ground stations within given areas, by providing discrete pulse characteristics.

Bearing mode selection is a pertinent air-to-air feature. In the inverse mode, the aircraft equipped with the rotating antenna obtains a reading to any other set transmitting an adequate pulse rate, while operating in the air-to-air mode. In effect, this feature permits installation of the analog rack at any remote site, from which an aircraft with digital rack may fly precise patterns controlled by the displayed range and bearing to that site. The rotating antenna presently in use at NAFEC is installed on Gulfstream N-47.

The rotating antenna is driven by the antenna drive unit, which provides precise 15-Hz driving signals to a synchronous motor in the rotating antenna. A reflecting element attached to a rotating drum rotates at a very precise 15 revolutions per second, which produces a 15-Hz cardioid radiation pattern in space that, when recovered, is a sinusoidally varying train of pulse amplitudes. Recovery of the 15-Hz component of the transmitted pulses along with a reference pulse, enables determination of relative bearing from one aircraft to another (figure 40).

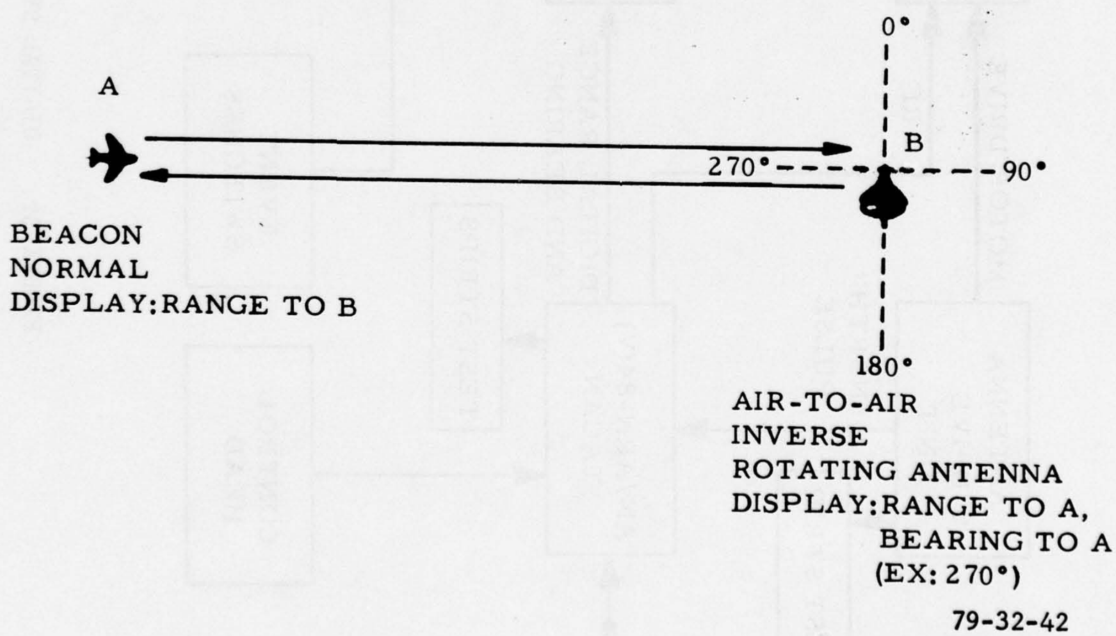

FIGURE 40. AIR-AIR, INVERSE MODE

The NAFEC installation does not use magnetic north signals for zero, but is aligned longitudinally to the aircraft so that dead-ahead is always zero degrees. In that manner, the equipped aircraft always knows the bearing of the other aircraft with respect to its present heading.

Controls at the formatter allow: (1) selection of data rates from one sample per second up to 10 samples per second, (2) thumbwheel switches to insert and record run numbers, and (3) numeric displays of range and bearing.

Up to three additional displays can be attached at other areas of the aircraft: in the cockpit, for example, to provide pilots with precise guidance to ground stations either air-air (with the analog rack) or air-ground; or the position of other aircraft involved in project flight tests. Resolution of the displays is to two decimal places in range (in nautical miles) and one decimal place in bearing (in degrees).

A six-switch module located on a flexible cable permits users to record event times by placing a mark on the tape at the instant a switch is placed on. Switch position status is displayed on the printed data listing, showing time within 0.1 second of operating the switch.

Each digital rack also has the capability to record up to eight channels of analog data.

Several minor hardware improvements have been added to the digital racks over a period of time based on operating experience. For example, there is an automatic antenna changeover capability for switching between upper and lower aircraft antennas when signal level drops suddenly, as in a banking maneuver. AGC from the receiver provides a transfer signal to actuate the antenna relay, although a defeat switch allows users to restrict operation to either selected antenna.

An AGC display was added to permit operators an input to assess signal conditions in flight. AGC and antenna status are recorded on the analog channels.

A test box permits access to 30 key signals from both the TACAN set and the antenna drive unit. Certain of these signals are reliable indicators of system performance in flight and provide the operator with a quick basis for deciding the need of in-flight action to improve data quality.

SYSTEM ACCURACY.

An accuracy test of the system was conducted and reported on in June 1977, in report No. FAA-RD-77-59, "Accuracy Test of an Air-to-Air Ranging and Bearing System." Range errors were obtained from comparison with phototheodolite data, while bearing measurements were compared against a periscopic sextant installed on the N-47 aircraft. (Relative bearing between two aircraft is extremely complex in the determination and cannot be done from ground-based systems, therefore the periscopic sextant.)

Bearing error was measured in two tests; first, a static test on the ground working against the analog system located approximately 0.7 nmi distant. Measurements were made on the ramp. Aircraft heading was changed to enable measurement at six different headings. Reference bearing measurements made with the sextant as compared to the TACAN-displayed bearing measurements were:

Mean Difference: 1.2°
Standard Deviation: 2.0°

These numbers compared quite favorably with design specifications, in view of the fact that TACAN utilizes a 15-Hz/135-Hz coarse/fine scheme for precision, whereas the N-47 antenna has only the coarse 15-Hz capability.

From controlled measurements, the average error of measure contributed by the sextant was estimated at 0.7°.

In a following flight test for bearing errors, two aircraft were positioned at several relative headings with respect to each other. Data were collected for periods in which the aircraft remained at the same nominal heading, since operation of the sextant under changing conditions of heading was impractical.

Combined differences from all headings resulted in:

Mean Difference: 0.8°
Standard Deviation: 2.4°.

In the range difference test, phototheodolite position data from two paired solutions were reduced to comparable slant range measurements on a flight in which the two aircraft maintained separations of 3 and 5 nmi. (NAFEC then had four phototheodolite stations in operation.) From a sample size of over 6,000 consecutive measurements, the statistics were:

Mean Difference: 6 feet
Standard Deviation: 100 feet.

Application of an optional smoothing filter to TACAN data reduced the standard deviation of differences to 60 feet. Modifications to the TACAN sets are expected to further reduce variability to less than 30 feet.

FUTURE IMPROVEMENTS.

Under contract to the manufacturer of the AN/ARN-84(V) sets, several modifications are designed to:

1. Track through interfering signals by implementation of a range-gated automatic gain modification.

2. Provide reduction in range resolution to 0.00315 nmi (19 feet) and bearing resolution to 0.125°.

3. Reduce range jitter through reduction in servo bandwidth (while retaining range rate tracking capability in excess of 1,000 knots).

4. Increase pulse rate to 2,700 pulses per second (pps) to permit full 15-Hz/135-Hz capability in the air-to-air mode.

DATA.

Two formats are available for the output data, as indicated in the data flow chart of figure 41. One of these, the standard listing, is commonly handed off as project data. The other format listing is designed as an aid to system performance analysis, properly interpreted.

An example of the standard listing report is shown in figure 42. The heading title is supplied by the program user to identify the output. Run number is the value recorded on tape from a two-digit switch located on the system formatter panel.

Print interval is the selected output time interval, and this value may be greater than the data sampling interval which is normally set during data collecton at 0.1 seconds (10/second sample rate). Optional interval printout reduces the size of output paper in scanning long runs.

When smoothing is selected, the range and bearing data printed in the report are values derived by smoothing the input data. The time constant of the smoothing filter is obtained from a value inputted to the filter and is approximately equal to the product of the input value and the sampling interval. If no smoothing is desired, the input value is placed to zero.

Data smoothing is accomplished by maintaining a position and rate estimate for range and bearing in which these estimates are corrected after each measurement. To avoid discrediting excessive data due to the filter's time constant, the estimate is coasted over invalid data for a time interval up to twice the filter input value. Further, the estimated rate is reset to zero whenever it exceeds program limits currently set to 2,400 knots or 30°/second velocities, which limits the effects of transients. Invalid data are registered on the printout with an asterisk preceding the invalid point, either range or bearing.

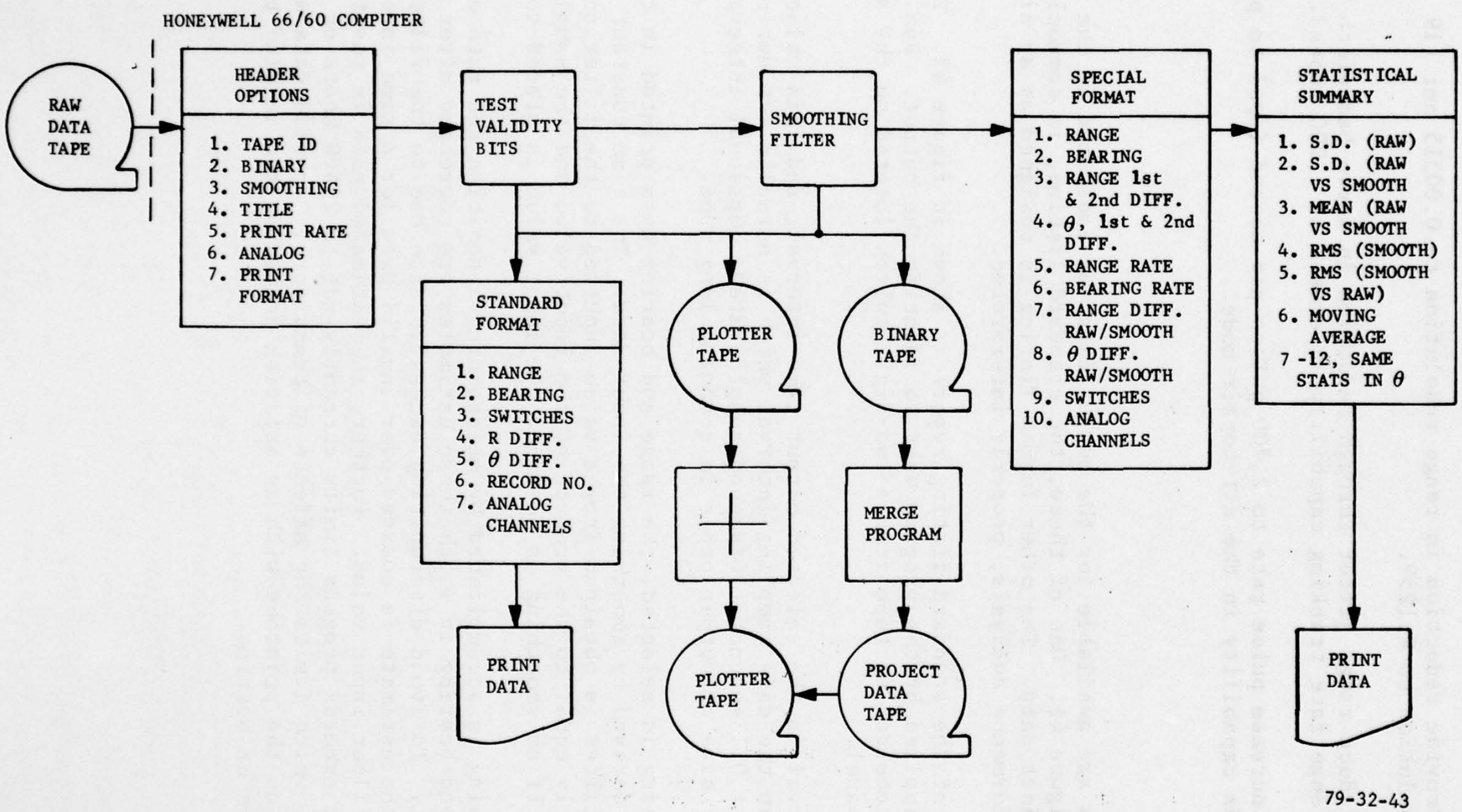

FIGURE 41. AIR-AIR SYSTEM DATA FLOW

AIR-AIR RANGING AND BEARING, SARASOTA TEST 12/18/78

RUN 2 FILE 1 PRINT INTERVAL 0.10 SMOOTHING K 5

TIME	TACAN RANGE	TACAN BEARING	SWITCH 1 2 3 4 5 6	RANGE CHANGE	BEARING CHANGE	RE-CORD	ANALOG 1	ANALOG 2	ANALOG 3	ANALOG 4	ANALOG 5	ANALOG 6	ANALOG 7	ANALCG 8
18 32 58.6	11.8804	9.69	1 1 1 1 1 1	-0.0065	0.02	391	2.496	0.013	0.580	0.122	0.050	0.159	0.444	0.968
18 32 58.7	11.8748	9.71	1 1 1 1 1 1	-0.0056	0.02	391	2.537	0.013	0.580	0.126	0.050	0.160	0.444	0.967
18 32 58.8	11.8721	9.72	1 1 1 1 1 1	-0.0027	0.02	391	2.510	0.013	0.581	0.129	0.053	0.161	0.444	0.957
18 32 58.9	11.8699	9.74	1 1 1 1 1 1	-0.0022	0.01	391	2.508	0.013	0.581	0.121	0.049	0.159	0.442	0.958
18 32 59.0	11.8744	9.71	1 1 1 1 1 1	0.0045	-0.03	391	2.462	0.013	0.580	0.127	0.050	0.160	0.442	0.958
18 32 59.1	11.8763	9.72	1 1 1 1 1 1	0.0019	0.01	391	2.481	0.013	0.579	0.127	0.051	0.161	0.443	0.967
18 32 59.2	11.8718	9.73	1 1 1 1 1 1	-0.0045	0.01	391	2.491	0.013	0.580	0.131	0.053	0.161	0.444	0.966
18 32 59.3	11.8680	9.79	1 1 1 1 1 1	-0.0038	0.05	391	2.523	0.013	0.581	0.133	0.055	0.162	0.446	0.963
18 32 59.4	11.8669	9.83	1 1 1 1 1 1	-0.0011	0.05	391	2.513	0.013	0.581	0.128	0.053	0.161	0.443	0.956
18 32 59.5	11.8598	9.87	1 1 1 1 1 1	-0.0071	0.04	391	2.498	0.013	0.580	0.128	0.053	0.162	0.443	0.956
18 32 59.6	11.8557	9.86	1 1 1 1 1 1	-0.0040	-0.01	391	2.451	0.013	0.580	0.127	0.051	0.161	0.441	0.957
18 32 59.7	11.8503	9.85	1 1 1 1 1 1	-0.0055	-0.01	391	2.448	0.013	0.580	0.127	0.050	0.160	0.441	0.961
18 32 59.8	11.8477	9.89	1 1 1 1 1 1	-0.0026	0.03	391	2.469	0.013	0.580	0.127	0.050	0.159	0.441	0.958
18 32 59.9	11.8435	9.92	1 1 1 1 1 1	-0.0042	0.03	391	2.503	0.013	0.580	0.123	0.049	0.158	0.440	0.952
18 33 0.0	11.8420	9.99	1 1 1 1 1 1	-0.0015	0.07	391	2.514	0.013	0.581	0.128	0.051	0.159	0.438	0.947
18 33 0.1	11.8367	10.04	1 1 1 1 1 1	-0.0053	0.06	391	2.505	0.013	0.580	0.127	0.051	0.160	0.438	0.952
18 33 0.2	11.8321	10.09	1 1 1 1 1 1	-0.0045	0.05	391	2.479	0.013	0.581	0.126	0.050	0.159	0.440	0.958
18 33 0.3	11.8283	10.14	1 1 1 1 1 1	-0.0038	0.04	391	2.505	0.013	0.580	0.127	0.051	0.160	0.443	0.969
18 33 0.4	11.8272	10.17	1 1 1 1 1 1	-0.0011	0.04	391	2.508	0.013	0.581	0.125	0.050	0.159	0.444	0.968
18 33 0.5	11.8159	10.20	1 1 1 1 1 1	-0.0113	0.03	391	2.554	0.013	0.580	0.125	0.049	0.160	0.444	0.968
18 33 0.6	11.8166	10.23	1 1 1 1 1 1	0.0007	0.03	391	2.535	0.012	0.580	0.123	0.048	0.158	0.443	0.960
18 33 0.7	11.8132	10.25	1 1 1 1 1 1	-0.0034	0.02	391	2.516	0.013	0.581	0.123	0.049	0.159	0.442	0.961
18 33 0.8	11.8103	10.27	1 1 1 1 1 1	-0.0029	0.02	391	2.495	0.013	0.580	0.126	0.050	0.160	0.443	0.963
18 33 0.9	11.8079	10.28	1 1 1 1 1 1	-0.0024	0.02	391	2.499	0.012	0.580	0.125	0.049	0.159	0.443	0.969
18 33 1.0	11.8081	10.34	1 1 1 1 1 1	0.0001	0.05	392	2.510	0.012	0.580	0.126	0.050	0.160	0.446	0.972
18 33 1.1	11.8083	10.38	1 1 1 1 1 1	0.0003	0.05	392	2.534	0.012	0.580	0.126	0.050	0.159	0.444	0.969
18 33 1.2	11.8024	10.42	1 1 1 1 1 1	-0.0059	0.04	392	2.567	0.013	0.580	0.126	0.050	0.160	0.446	0.969
18 33 1.3	11.7995	10.46	1 1 1 1 1 1	-0.0030	0.03	392	2.562	0.013	0.581	0.134	0.056	0.164	0.448	0.968
18 33 1.4	11.7949	10.44	1 1 1 1 1 1	-0.0045	-0.01	392	2.552	0.013	0.581	0.132	0.055	0.165	0.449	0.971
18 33 1.5	11.7932	10.43	1 1 1 1 1 1	-0.0018	-0.01	392	2.519	0.013	0.580	0.132	0.056	0.165	0.449	0.972
18 33 1.6	11.7959	10.46	1 1 1 1 1 1	0.0028	0.03	392	2.552	0.013	0.580	0.125	0.051	0.164	0.449	0.984
18 33 1.7	11.7922	10.49	1 1 1 1 1 1	-0.0037	0.03	392	2.569	0.013	0.581	0.127	0.051	0.162	0.452	0.984
18 33 1.8	11.7828	10.55	1 1 1 1 1 1	-0.0094	0.06	392	2.612	0.013	0.580	0.126	0.050	0.162	0.451	0.983
18 33 1.9	11.7747	10.60	1 1 1 1 1 1	-0.0081	0.05	392	2.614	0.013	0.581	0.125	0.049	0.161	0.449	0.979
18 33 2.0	11.7657	10.65	1 1 1 1 1 1	-0.0090	0.05	392	2.606	0.013	0.580	0.128	0.053	0.164	0.451	0.980
18 33 2.1	11.7642	10.69	1 1 1 1 1 1	-0.0015	0.04	392	2.597	0.013	0.571	0.125	0.051	0.164	0.453	0.987
18 33 2.2	11.7589	10.68	1 1 1 1 1 1	-0.0053	-0.01	392	2.571	0.012	0.579	0.123	0.051	0.164	0.453	0.994
18 33 2.3	11.7503	10.67	1 1 1 1 1 1	-0.0087	-0.01	392	2.584	0.012	0.580	0.125	0.050	0.164	0.455	0.998
18 33 2.4	11.7429	10.62	1 1 1 1 1 1	-0.0074	-0.05	392	2.589	0.012	0.580	0.125	0.051	0.162	0.455	0.996
18 33 2.5	11.7345	10.57	1 1 1 1 1 1	-0.0084	-0.04	392	2.621	0.013	0.580	0.133	0.057	0.167	0.459	0.995
18 33 2.6	11.7315	10.58	1 1 1 1 1 1	-0.0030	0.00	392	2.600	0.012	0.580	0.128	0.054	0.165	0.457	0.984
18 33 2.7	11.7269	10.62	1 1 1 1 1 1	-0.0045	0.04	392	2.578	0.013	0.580	0.129	0.054	0.166	0.455	0.985
18 33 2.8	11.7190	10.70	1 1 1 1 1 1	-0.0080	0.08	392	2.541	0.012	0.580	0.128	0.054	0.166	0.454	0.985
18 33 2.9	11.7143	10.77	1 1 1 1 1 1	-0.0047	0.07	392	2.527	0.012	0.579	0.129	0.055	0.166	0.454	0.988
18 33 3.0	11.7083	10.78	1 1 1 1 1 1	-0.0060	0.02	392	2.529	0.012	0.579	0.132	0.055	0.166	0.454	0.985
18 33 3.1	11.7032	10.80	1 1 1 1 1 1	-0.0051	0.01	392	2.531	0.012	0.580	0.128	0.054	0.164	0.452	0.980
18 33 3.2	11.6969	10.81	1 1 1 1 1 1	-0.0063	0.01	392	2.563	0.013	0.579	0.126	0.051	0.162	0.451	0.974
18 33 3.3	11.6915	10.86	1 1 1 1 1 1	-0.0053	0.05	392	2.536	0.013	0.581	0.128	0.053	0.161	0.448	0.966
18 33 3.4	11.6850	10.90	1 1 1 1 1 1	-0.0066	0.04	392	2.525	0.013	0.580	0.128	0.054	0.164	0.447	0.967
18 33 3.5	11.6836	10.94	1 1 1 1 1 1	-0.0014	0.04	392	2.482	0.012	0.580	0.128	0.053	0.162	0.447	0.968

79-32-44

FIGURE 42. SAMPLE PRODUCTION FORMAT DATA LISTING

A first-difference change in range and bearing between consecutive samples is also printed as an aid in quality review of data. Velocity data are more sensitive to change than position data, therefore a scan of first differences (velocity at the interval rate) provides an insight into data variability.

On the remainder of the standard format is a status list of the six sense switches, record number of data, and printout of any analog channels uses.

A special format may be substituted for the standard format, an example of which is shown in figure 43. In this, the first and second differences of range and bearing are printed along with the estimated velocity relative to the cooperating aircraft, and the differences between raw and smoothed range and bearing data.

Immediately following data listings in the special format are statistical summary pages for each run (figure 44). These statistics, not intended for general use, include standard deviations of raw data, mean and standard deviations of differences between raw and smoothed data, root mean square (RMS) error of smoothed data, a reduction factor as a ratio of smoothed standard deviation to raw standard deviation, and moving averages of this reduction factor. Properly interpreted, these statistics provide the basis upon which data quality can be quickly and readily assessed. Since a single input filter constant cannot accommodate all rates of changes experienced in a given test flight, there is the potential within the software for determining a moving smoothing factor based on these computations of data variability.

A binary output tape is provided for use as input to other computer programs in a form that is easier to process than the data on the raw data tape. This binary tape is a nine-track, 800 bits per inch (bpi) tape written with an unformatted Fortran write statement. The binary format presents the time word, range in nautical mile, and bearing in degrees. If either range or bearing are invalid in a given sample, that value of range or bearing is made negative as an indication to users to omit that value.

System specifications are given in table 8.

AIR AIR RANGING AND BEARING, SARASOTA TEST 12/19/78

AIR-TO-AIR RANGE AND BEARING SYSTEM

RUN 2 FILE 1 K 5

TIME	RANGE (NMI)	BEARING (DEG)	DEL1 (R)	DEL2 (R)	DEL1 (B)	DEL2 (B)	REC. NO.	SWITCH 123456	RRATE KNOTS	BRATE DEG/S	A N A L O G 1	A N A L O G 2	RO-RK	BO-BK
18 32 58.6	11.8804	9.69	-0.0065	-0.0013	0.02	-0.00	391	111111	-112.8	0.10	2.4957	0.0134	-0.0179	0.12
18 32 58.7	11.8748	9.71	-0.0056	0.0010	0.02	-0.00	391	111111	-116.8	0.11	2.5372	0.0134	-0.0123	0.09
18 32 58.8	11.8721	9.72	-0.0027	0.0029	0.02	-0.00	391	111111	-115.8	0.11	2.5104	0.0134	0.0029	0.05
18 32 58.9	11.8699	9.74	-0.0022	0.0005	0.01	-0.00	391	111111	-114.2	0.11	2.5079	0.0134	0.0051	0.03
18 32 59.0	11.8744	9.71	0.0045	0.0067	-0.03	-0.04	391	111111	-101.7	0.09	2.4615	0.0134	0.0381	-0.41
18 32 59.1	11.8763	9.72	0.0019	-0.0025	0.01	0.05	391	111111	-93.9	0.09	2.4811	0.0134	0.0237	0.06
18 32 59.2	11.8718	9.73	-0.0045	-0.0064	0.01	-0.00	391	111111	-96.9	0.09	2.4908	0.0134	-0.0093	0.03
18 32 59.3	11.8680	9.79	-0.0038	0.0007	0.05	0.04	391	111111	-98.8	0.11	2.5226	0.0134	-0.0055	0.43
18 32 59.4	11.8662	9.83	-0.0011	0.0027	0.05	-0.01	391	111111	-96.1	0.13	2.5128	0.0134	0.0081	0.34
18 32 59.5	11.8598	9.87	-0.0071	-0.0060	0.04	-0.01	391	111111	-103.4	0.14	2.4982	0.0134	-0.0223	0.26
18 32 59.6	11.8557	9.86	-0.0040	0.0031	-0.01	-0.05	391	111111	-105.3	0.13	2.4505	0.0134	-0.0057	-0.22
18 32 59.7	11.8503	9.85	-0.0055	-0.0015	-0.01	0.00	391	111111	-109.5	0.12	2.4481	0.0134	-0.0128	-0.21
18 32 59.8	11.8477	9.89	-0.0026	0.0029	0.03	0.04	391	111111	-108.7	0.13	2.4689	0.0134	0.0023	0.22
18 32 59.9	11.8435	9.92	-0.0042	-0.0016	0.03	-0.00	391	111111	-110.7	0.14	2.5031	0.0134	-0.0060	0.16
18 33 0.0	11.8420	9.99	-0.0015	0.0027	0.07	0.04	391	111111	-108.0	0.16	2.5140	0.0134	0.0080	0.53
18 33 0.1	11.8367	10.04	-0.0053	-0.0039	0.06	-0.01	391	111111	-111.9	0.18	2.5055	0.0134	-0.0117	0.41
18 33 0.2	11.8321	10.09	-0.0045	0.0008	0.05	-0.01	391	111111	-114.2	0.20	2.4786	0.0134	-0.0071	0.31
18 33 0.3	11.8283	10.14	-0.0038	0.0007	0.04	-0.01	391	111111	-115.3	0.21	2.5055	0.0134	-0.0033	0.23
18 33 0.4	11.8272	10.17	-0.0011	0.0027	0.04	-0.01	391	111111	-111.9	0.21	2.5079	0.0134	0.0103	0.16
18 33 0.5	11.8159	10.20	-0.0113	-0.0101	0.03	-0.01	391	111111	-125.3	0.22	2.5543	0.0134	-0.0409	0.09
18 33 0.6	11.8166	10.23	0.0007	0.0120	0.03	-0.00	391	111111	-118.5	0.22	2.5348	0.0122	0.0209	0.04
18 33 0.7	11.8132	10.25	-0.0034	-0.0041	0.02	-0.00	391	111111	-118.7	0.22	2.5165	0.0134	-0.0007	-0.00
18 33 0.8	11.8103	10.27	-0.0029	0.0006	0.02	-0.00	391	111111	-118.0	0.22	2.4945	0.0134	0.0022	-0.04
18 33 0.9	11.8079	10.28	-0.0024	0.0005	0.02	-0.00	391	111111	-116.5	0.22	2.4994	0.0122	0.0046	-0.07
18 33 1.0	11.8081	10.34	0.0001	0.0025	0.05	0.04	392	111111	-110.9	0.23	2.5104	0.0122	0.0169	0.32
18 33 1.1	11.8083	10.38	0.0003	0.0001	0.05	-0.01	392	111111	-105.4	0.24	2.5336	0.0122	0.0167	0.23
18 33 1.2	11.8024	10.42	-0.0059	-0.0062	0.04	-0.01	392	111111	-110.3	0.25	2.5665	0.0134	-0.0149	0.15
18 33 1.3	11.7995	10.46	-0.0030	0.0030	0.03	-0.01	392	111111	-110.2	0.25	2.5617	0.0134	0.0005	0.09
18 33 1.4	11.7949	10.44	-0.0045	-0.0016	-0.01	-0.05	392	111111	-112.6	0.23	2.5519	0.0134	-0.0074	-0.39
18 33 1.5	11.7932	10.43	-0.0018	0.0028	-0.01	0.00	392	111111	-110.4	0.22	2.5189	0.0134	0.0068	-0.36
18 33 1.6	11.7952	10.46	0.0028	0.0045	0.03	0.04	392	111111	-100.8	0.22	2.5519	0.0134	0.0291	0.08
18 33 1.7	11.7922	10.49	-0.0037	-0.0065	0.03	-0.00	392	111111	-102.3	0.22	2.5690	0.0134	-0.0047	0.03
18 33 1.8	11.7828	10.55	-0.0094	-0.0057	0.06	0.04	392	111111	-113.1	0.24	2.6117	0.0134	-0.0328	0.40
18 33 1.9	11.7747	10.60	-0.0081	0.0013	0.05	-0.01	392	111111	-121.2	0.25	2.6142	0.0134	-0.0247	0.30
18 33 2.0	11.7657	10.65	-0.0090	-0.0009	0.05	-0.01	392	111111	-130.4	0.26	2.6056	0.0134	-0.0282	0.20
18 33 2.1	11.7642	10.69	-0.0015	0.0075	0.04	-0.01	392	111111	-126.9	0.27	2.5971	0.0134	0.0108	0.13
18 33 2.2	11.7589	10.68	-0.0053	-0.0038	-0.01	-0.05	392	111111	-129.8	0.25	2.5714	0.0122	-0.0089	-0.36
18 33 2.3	11.7503	10.67	-0.0087	-0.0033	-0.01	0.00	392	111111	-138.1	0.24	2.5836	0.0122	-0.0253	-0.34
18 33 2.4	11.7429	10.62	-0.0074	0.0013	-0.05	-0.04	392	111111	-144.0	0.20	2.5885	0.0122	-0.0179	-0.74
18 33 2.5	11.7345	10.57	-0.0084	-0.0010	-0.04	0.01	392	111111	-151.2	0.17	2.6215	0.0134	-0.0220	-0.65
18 33 2.6	11.7315	10.58	-0.0030	0.0054	0.00	0.05	392	111111	-149.2	0.17	2.5995	0.0122	0.0060	-0.15
18 33 2.7	11.7262	10.62	-0.0045	-0.0015	0.04	0.04	392	111111	-149.8	0.18	2.5775	0.0134	-0.0019	0.26
18 33 2.8	11.7120	10.70	-0.0180	-0.0134	0.08	0.04	392	111111	-156.1	0.21	2.5409	0.0122	-0.0190	0.60
18 33 2.9	11.7143	10.77	-0.0047	0.0033	0.07	-0.01	392	111111	-156.6	0.23	2.5275	0.0122	-0.0018	0.47
18 33 3.0	11.7083	10.78	-0.0060	-0.0013	0.02	-0.05	392	111111	-159.4	0.23	2.5287	0.0122	-0.0083	-0.06
18 33 3.1	11.7032	10.80	-0.0051	0.0009	0.01	-0.00	392	111111	-160.4	0.22	2.5311	0.0122	-0.0032	-0.09
18 33 3.2	11.6962	10.81	-0.0063	-0.0013	0.01	-0.00	392	111111	-163.5	0.22	2.5629	0.0134	-0.0094	-0.11
18 33 3.3	11.6915	10.86	-0.0053	0.0010	0.05	0.04	392	111111	-164.8	0.23	2.5360	0.0134	-0.0040	0.29
18 33 3.4	11.6850	10.90	-0.0066	-0.0012	0.04	-0.01	392	111111	-168.1	0.24	2.5250	0.0134	-0.0100	0.20
18 33 3.5	11.6836	10.94	-0.0014	0.0052	0.04	-0.01	392	111111	-162.7	0.24	2.4823	0.0122	0.0164	0.13

79-32-45

FIGURE 43. SAMPLE SPECIAL FORMAT DATA LISTING

RUN 2 FILE 1 K 5

RECORD NUMBER	RANGE DATA S-O	RANGE DATA S-O,K	RANGE DATA X-O,K	RANGE DATA RMSE-K	RANGE DATA RDEF-K	RANGE DATA SRED	RECORD NUMBER	BEARING DATA S-O	BEARING DATA S-O,K	BEARING DATA X-O,K	BEARING DATA RMSE-K	BEARING DATA RDEF-K	BEARING DATA SRED	RUN
386	0.026	0.033	-0.007	0.021	0.815	0.754	386	0.15	0.41	-0.08	0.39	2.62	2.30	2
387	0.021	0.039	-0.005	0.033	1.570	1.075	387	0.33	1.24	0.05	1.20	3.67	2.83	2
388	0.012	0.021	0.005	0.018	1.483	1.282	388	0.10	0.34	0.03	0.32	3.39	3.23	2
389	0.017	0.016	-0.004	0.008	0.473	1.175	389	0.10	0.27	-0.05	0.25	2.38	3.15	2
390	0.017	0.015	-0.002	0.008	0.505	0.820	390	0.11	0.29	0.06	0.27	2.44	2.73	2
391	0.020	0.016	-0.000	0.012	0.607	0.528	391	0.09	0.20	-0.06	0.19	2.28	2.36	2
392	0.019	0.017	-0.003	0.008	0.414	0.509	392	0.09	0.17	0.01	0.15	1.74	2.15	2
393	0.011	0.014	-0.002	0.008	0.682	0.570	393	0.08	0.21	-0.06	0.20	2.43	2.15	2
394	0.021	0.020	-0.002	0.007	0.341	0.481	394	0.08	0.16	0.05	0.15	1.82	2.00	2
395	0.022	0.033	0.001	0.024	1.085	0.705	395	0.07	0.19	-0.04	0.18	2.37	2.20	2
396	0.012	0.016	-0.004	0.011	0.936	0.787	396	0.09	0.24	-0.03	0.22	2.63	2.27	2
397	0.020	0.017	0.001	0.010	0.520	0.847	397	0.06	0.13	0.01	0.12	1.82	2.27	2
398	0.021	0.021	0.001	0.002	0.089	0.515	398	0.09	0.10	0.04	0.07	0.78	1.74	2
399	0.025	0.057	-0.007	0.052	2.086	0.398	399	0.07	0.07	-0.06	0.06	0.92	1.17	3
400	0.027	0.024	0.005	0.013	0.497	0.391	400	0.08	0.12	0.04	0.10	1.14	0.75	3
401	0.021	0.022	-0.002	0.006	0.310	0.264	401	0.07	0.12	0.02	0.09	1.30	1.12	3
402	0.016	0.016	0.003	0.003	0.213	0.340	402	0.07	0.24	-0.08	0.24	3.27	1.90	3
403	0.028	0.023	0.000	0.015	0.536	0.353	403	0.07	0.15	0.10	0.17	2.38	2.31	3
404	0.021	0.016	-0.000	0.014	0.637	0.462	404	0.15	0.45	-0.01	0.42	2.93	2.86	3
405	0.024	0.022	0.002	0.011	0.457	0.543	405	0.07	0.17	0.04	0.16	2.25	2.52	3
406	0.027	0.019	-0.001	0.019	0.701	0.598	406	0.16	0.53	-0.07	0.51	3.19	2.79	3
407	0.026	0.021	-0.001	0.016	0.526	0.585	407	0.11	0.35	0.00	0.33	2.89	2.78	3
408	0.022	0.017	0.001	0.013	0.618	0.638	408	0.08	0.19	-0.02	0.18	2.17	2.75	3
409	0.015	0.013	0.000	0.008	0.501	0.572	409	0.09	0.20	0.02	0.18	2.13	2.40	3
410	0.015	0.017	0.007	0.009	0.647	0.589	410	0.09	0.17	0.01	0.15	1.77	2.02	3
411	0.029	0.022	-0.003	0.019	0.560	0.603	411	0.08	0.18	-0.00	0.16	2.06	1.99	3
412	0.022	0.018	0.001	0.013	0.592	0.633	412	0.09	0.17	-0.04	0.15	1.69	1.84	3
413	0.019	0.016	0.001	0.010	0.507	0.586	413	0.07	0.12	0.02	0.10	1.39	1.71	3
414	0.020	0.021	-0.002	0.008	0.393	0.497	414	0.07	0.16	0.03	0.15	2.21	1.76	3
415	0.023	0.020	0.001	0.012	0.528	0.476	415	0.07	0.12	-0.03	0.10	1.49	1.70	3
416	0.019	0.015	-0.000	0.011	0.596	0.506	416	0.06	0.13	0.00	0.11	1.75	1.82	3
417	0.013	0.018	0.004	0.014	1.109	0.745	417	0.08	0.14	-0.02	0.12	1.54	1.59	3
418	0.017	0.016	-0.003	0.007	0.437	0.714	418	0.04	0.08	-0.00	0.07	1.65	1.55	3
419	0.021	0.020	0.000	0.004	0.209	0.585	419	0.04	0.07	0.05	0.08	1.93	1.71	3
420	0.020	0.017	0.001	0.011	0.553	0.400	420	0.08	0.13	-0.06	0.11	1.39	1.66	3
421	0.025	0.018	-0.002	0.017	0.691	0.494	421	0.07	0.12	0.01	0.10	1.36	1.56	3
422	0.020	0.016	0.000	0.012	0.621	0.621	422	0.05	0.09	-0.01	0.07	1.41	1.39	3
423	0.025	0.020	0.001	0.014	0.564	0.625	423	0.02	0.05	0.03	0.05	2.06	1.61	3
424	0.017	0.016	0.001	0.005	0.321	0.502	424	0.06	0.15	-0.06	0.15	2.31	1.93	3
425	0.016	0.020	-0.001	0.011	0.716	0.534	425	0.07	0.13	0.06	0.12	1.77	2.05	3
426	0.015	0.014	0.002	0.004	0.274	0.437	426	0.08	0.15	0.04	0.14	1.79	1.96	3
427	0.016	0.014	-0.001	0.008	0.479	0.490	427	0.06	0.15	-0.03	0.15	2.42	1.99	3
428	0.027	0.022	0.000	0.017	0.607	0.453	428	0.06	0.13	0.01	0.12	1.94	2.05	3
429	0.018	0.015	0.002	0.010	0.565	0.550	429	0.08	0.18	-0.03	0.16	1.93	2.10	3
430	0.012	0.013	-0.001	0.005	0.422	0.531	430	0.06	0.09	0.01	0.06	1.07	1.65	3
431	0.018	0.017	-0.000	0.004	0.197	0.395	431	0.06	0.17	0.05	0.17	2.75	1.92	3
432	0.020	0.020	0.003	0.004	0.184	0.268	432	0.06	0.32	-0.03	0.32	5.10	2.97	3
433	0.023	0.029	-0.003	0.018	0.783	0.388	433	0.06	0.19	0.01	0.13	2.91	3.59	3
434	0.018	0.017	0.002	0.007	0.402	0.456	434	0.09	0.26	0.10	0.26	3.03	3.68	3
435	0.019	0.018	0.002	0.008	0.395	0.527	435	0.09	0.32	-0.19	0.36	3.99	3.31	3
436	0.022	0.018	-0.001	0.013	0.584	0.460	436	0.08	0.23	0.16	0.27	3.20	3.41	3
437	0.014	0.012	0.002	0.006	0.445	0.475	437	0.10	0.35	-0.06	0.34	3.51	3.57	3
438	0.020	0.018	0.003	0.010	0.496	0.508	438	0.10	0.40	0.14	0.41	3.95	3.56	3
439	0.025	0.023	-0.001	0.012	0.463	0.468	439	0.15	0.83	0.61	1.02	6.79	4.75	3

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FIGURE 44. SAMPLE STATISTICAL SUMMARY LISTING

TABLE 8. TACAN (AN/ARN-84V) SPECIFICATIONS

LEADING PARTICULAR	CHARACTERISTICS
Frequency Range	1025 MHz to 1150 MHz, transmit 962 MHz to 1213 MHz, receive
Channels	1 to 126, air-ground or air-air
Modes	X mode or Y mode, selectable
Power Output	1.5 kW minimum, 4 kW maximum
Input Power	115 V a.c., 400 Hz, 28 V d.c.
Receiver Sensitivity	-98 dBm
Maximum Range	200 nmi
Aircraft Limits	Ranging between maximum of five aircraft
Bearing Limits	Rotating antenna for 15 Hz modulation on N-47. Any number aircraft may receive inverse bearings
Pulse Characteristics	
Rise Time	2.5 $\pm$0.1 μs
Pulse Pair Spacing	
X Mode	12 μs
Y Mode	36 μs
Transponder Delay	50 μs $\pm$ 0.1 μs
Air-Air Delay	62 μs $\pm$ 0.1 μs
Pulse Repetition Rate	
Search	142 to 150 pulse pairs/second
Track	22 to 30 pulse pairs/second
Digital resolution	
Range	20 feet
Bearing	0.125°
System Error	
Range	30 feet
Bearing	0.5°

RANGE CONTROL CENTRAL FACILITY

The Range Control facility integrates the collection, processing, and recording of all phototheodolite data and, additionally, serves as focal point in coordinating the activities of test flights using other range instrumentation facilities (table 9). Range Control provides the central timing equipment that is distributed to all other facilities, including remote sites and aircraft systems; provides the equipment for air-ground communications between range facilities and test aircraft; contains the phototheodolite real-time display and recording system, and a General Automation computer with 120-column printer.

TIMING.

The time-code generators of the central timing system produce real-time codes consisting of sequences of serial pulses in BCD d.c. level shift and modulated code representations of time. These codes are in both IRIG-B and a special-format NAFEC time code.

The NAFEC code is produced in units, or frames, each of which consists of 10 decades. Figure 45 illustrates the NAFEC time code. Eight of the ten decades are used to provide real-time code; the tenth decade contains frame marker pulses. Available from rates are at 20/second, 10/second, 5/second, 1/second, and 1/ten seconds.

The IRIG-B format is illustrated in figure 46.

UHF frequency modulation (FM) transmitters are used to transmit control pulses and real-time code to airborne terminal timing units in the aircraft. Both NAFEC time and IRIG-B are transmitted to several project sites at NAFEC.

COMMUNICATIONS.

Direct communications circuits connect the supervisor's console with the other range facilities, with the NAFEC tower, and with test aircraft. Hard-wire patching of the timing and communications signals is used to set up communication circuits from the operator's console to the phototheodolite towers to enable direct control of phototheodolite tracking activities.

Various VHF/UHF transmitter-receiver equipments are available. These assigned communications frequencies are also available to test personnel at remote locations via telephone circuits. This feature permits project personnel to monitor and participate in test activities without the need for direct installation of communications equipment at the ground site.

Several types of airborne timing units are used in project equipment. These are synchronized to a portable time-code generator that serves as master to the project system time code generator(s). The portable unit is normally

TABLE 9. RANGE CONTROL SPECIFICATIONS

LEADING PARTICULAR	CHARACTERISTIC
Timing Code Generator	
Real-Time Code	1 frame per 10 seconds 1 frame per second 5 frames per second 10 frames per second 20 frames per second
Control Pulse Rates	1,000 pulses per second 20 pulses per second 10 pulses per second 5 pulses per second 1 pulse per second 1 pulse per 10 seconds 1 pulse per 30 seconds 1 pulse per 60 seconds 1 pulse per 120 seconds
IRIG-B	Modulated and d.c. level slow code
Multiplex Signal	
Serial Real-Time Code	1 frame per 10 seconds 1 frame per second
Parallel Real-Time Code	1 frame per second 5 frames per second, or 10 frames per second
Control Tones	2 kilocycles 4 kilocycles
Airborne Terminal Timing Unit, Slave Type	
Frequency	410.65 megacycles
Number of Units	7
Airborne Terminal Timing Unit, Synchronized Type	
Real-Time Code Rates	1 frame per 10 seconds
Serial	1 frame per second
Parallel	1 frame per second, 5 frames per second, or 10 frames per second
Control Pulse Rates	100 pulses per second 20 pulses per second 10 pulses per second 5 pulses per second 1 pulse per second 1 pulse per 10 seconds

TABLE 9. RANGE CONTROL SPECIFICATIONS (Continued)

LEADING PARTICULAR	CHARACTERISTIC
Real-Time Code Rates	
Bipolar	10 frames per second
	1 frame per second
	1 frame per 10 seconds
	1 frame per minute
Unipolar	10 frames per second
	1 frame per second
	1 frame per 10 seconds
	1 frame per minute
Control Pulse Rates	10 pulses per second
	1 pulse per second
	1 pulse per 10 seconds
	1 pulse per 30 seconds
	1 pulse per minute

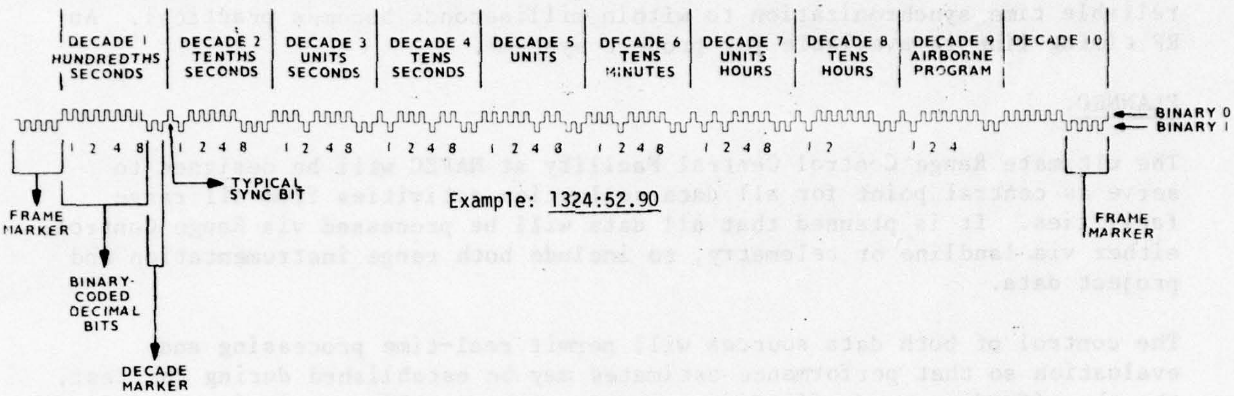

FIGURE 45. NAFEC TIME CODE

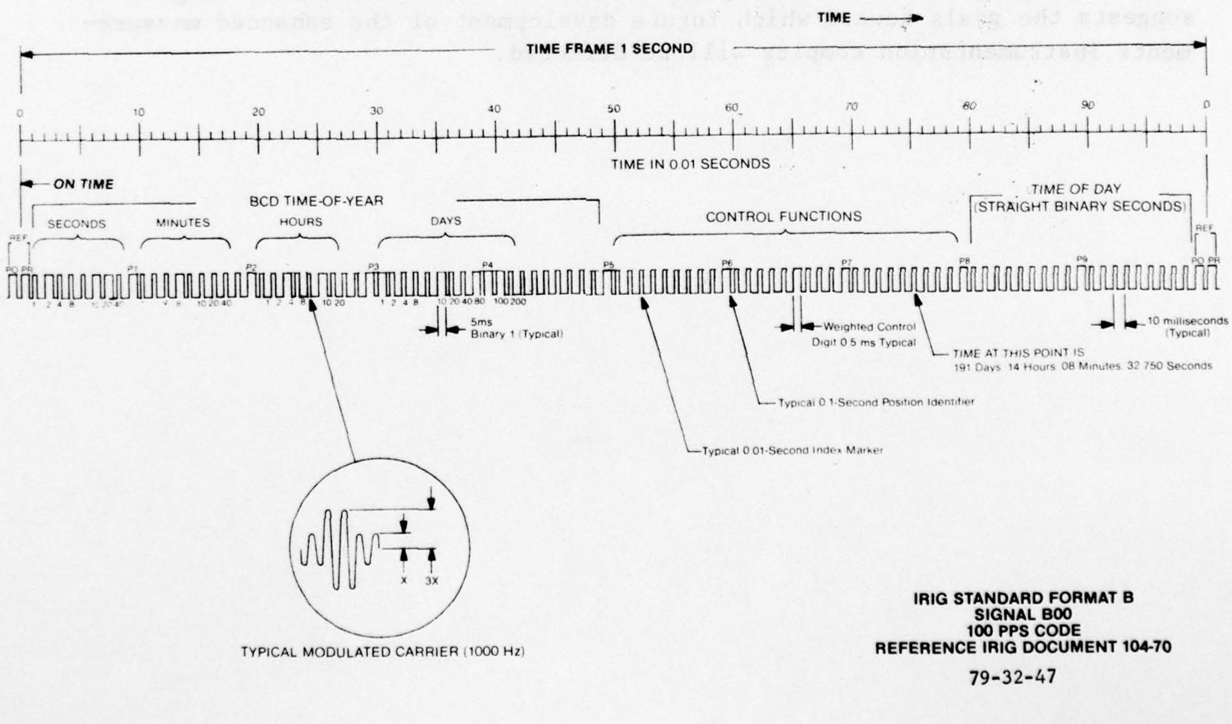

FIGURE 46. IRIG-B FORMAT

synchronized to the master time code from Range Control at various field locations where the central time is available via landline. In this manner, reliable time synchronization to within milliseconds becomes practical. An RF timing line is available for project systems.

PLANNED.

The ultimate Range Control Central Facility at NAFEC will be designed to serve as central point for all data collection activities from all range facilities. It is planned that all data will be processed via Range Control, either via landline or telemetry, to include both range instrumentation and project data.

The control of both data sources will permit real-time processing and evaluation so that performance estimates may be established during the test, thereby affording more effective systems use by enabling real-time decisions of project system performance.

Various real-time data management and display devices will be incorporated in the ultimate system, to include: data computations and printout, generation of plots of either raw data or project data versus reference instrumentation data, television displays, "smart" terminal for interaction with the NAFEC computer during test activities, and various other improvements. Figure 47 suggests the goals toward which future development of the enhanced measurements instrumentation complex will be directed.

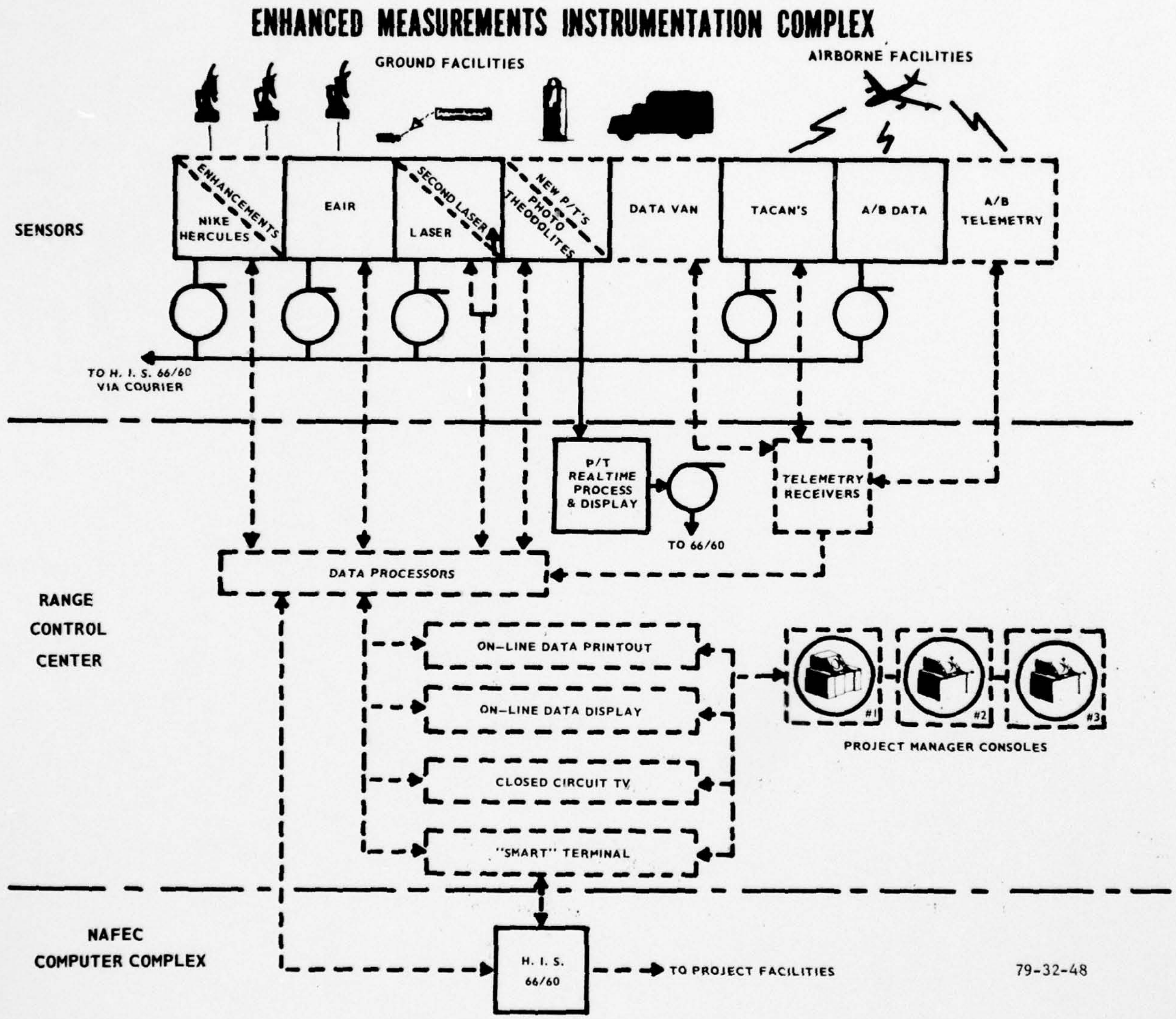

FIGURE 47. ENHANCED MEASUREMENTS INSTRUMENTATION COMPLEX

AD-A082 063 NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER ATL--ETC F/G 14/2
NAFEC RANGE INSTRUMENTATION SYSTEMS, (U)
FEB 80 V J LUCIANI
UNCLASSIFIED FAA-NA-79-32 NL

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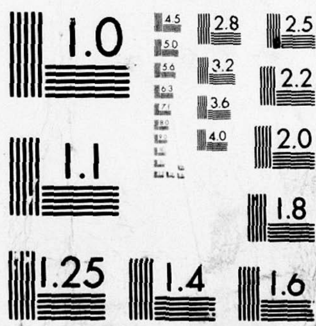

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX

PHOTOTHEODOLITE ERROR DEFINITION

The prime factor in phototheodolite system accuracy is the location of the target with respect to the baseline bisector; which is why d is called the "location" error factor. Lengthy derivations of d, as given in the Fecker report, are based on the premise that, for small values of e, quadrilateral QSRT (figure A-1) can be treated as a parallelogram.

This parallelogram is formed by the intersection of the lines of angular uncertainty from each phototheodolite, and encompasses at its center, the true target position, P.

From the Fecker algorithms, two values of d are given:

$$d_1 = \frac{\sqrt{\left[y^2 + (1 + x)^2\right]\left[y^2 + (1 - x)^2\right]}}{2y} \qquad (1)$$

and

$$d_2 = d_1 \sqrt{x^2 + y^2} \qquad (2)$$

where:

$$x = \frac{X}{B/2} \text{ and } y = \frac{Y}{B/2} \qquad (3)$$

in which X,Y are target coordinates with respect to the midpoint of the selected baseline.

If d has two values, d_1 and d_2, then E must have two values. These two values of E are displayed in figure A-1 as lines QP and SP. By definition, however, E will be the larger of the two values computed and will be computed using the larger of d_1 or d_2. For example, whenever the target is located outside an area prescribed by a circle whose diameter is the baseline distance, d_2 will be found to be larger than d_1. In figure A-1, the error so computed will be the line SP.

It is appropriate to note that SP is a longitudinal error, in the same direction as a line from the baseline's midpoint to the target. (If the target is on the baseline bisector, the error computed using d_2 is along the Y axis.)

Line QP, on the other hand, is computed using d_1 and is a lateral error. Should lateral error be a more important measurement than longitudinal error, then the computation of E should use d_1 rather than d_2. But to repeat a

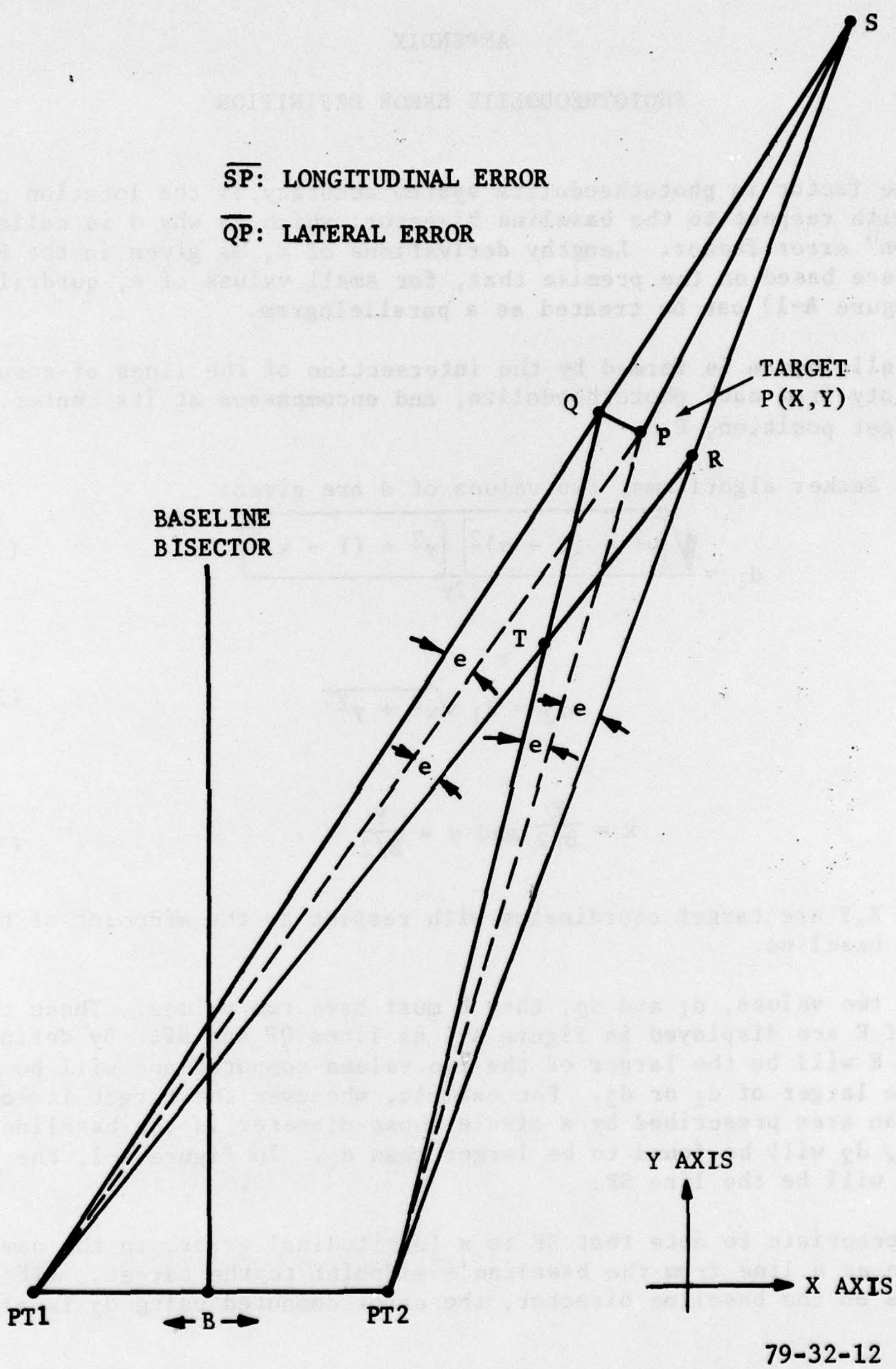

FIGURE A-1. ERROR GEOMETRY

previous statement, E, in the chart, is defined as the maximum potential error and will always use the larger of d_1, d_2.

Within a circle whose diameter is the baseline distance, d_1 will always be larger than d_2. In consequence, the lateral error, close in, will always exceed the longitudinal error; i.e., line QP of figure A-1 will be larger than line SP.

The charts of figures 10 and 11 show only the larger of d_1 or d_2, regardless whether the target is within or outside the baseline-diameter circle. However, to investigate each dimension of error, the following description redefines E in terms of both longitudinal and lateral errors. In this, E_1 is the maximum potential lateral error found by using d_1; E_2 is the maximum potential longitudinal error found by using d_2.

The terms d_1 and d_2 can be expressed more meaningfully. Referring to figure A-2:

$$R_1 = \sqrt{Y^2 + (B/2 + X)^2} = B/2\sqrt{y^2 + (1 + x)^2} = A_1(B/2), \tag{4}$$

$$R_2 = \sqrt{Y^2 + (B/2 - X)^2} = B/2\sqrt{y^2 + (1 - x)^2} = A_2(B/2). \tag{5}$$

The area of the triangle with sides B, R_1, R_2 is

$$\text{area} = R_1R_2\mathrm{Sin}\theta/2, \tag{6}$$

and

$$\text{area} = BY/2. \tag{7}$$

Setting these equal,

$$\frac{R_1R_2\mathrm{Sin}\theta}{2} = \frac{BY}{2}\ . \tag{8}$$

Substituting for R_1, R_2, and Y, from equations (3), (4), and (5), equation (8) yields

$$\frac{(A_1B/2)(A_2B/2)\mathrm{Sin}\theta}{2} = \frac{B[y(B/2)]}{2} \tag{9}$$

or

$$\frac{A_1A_2\mathrm{Sin}\theta}{2} = y \tag{10}$$

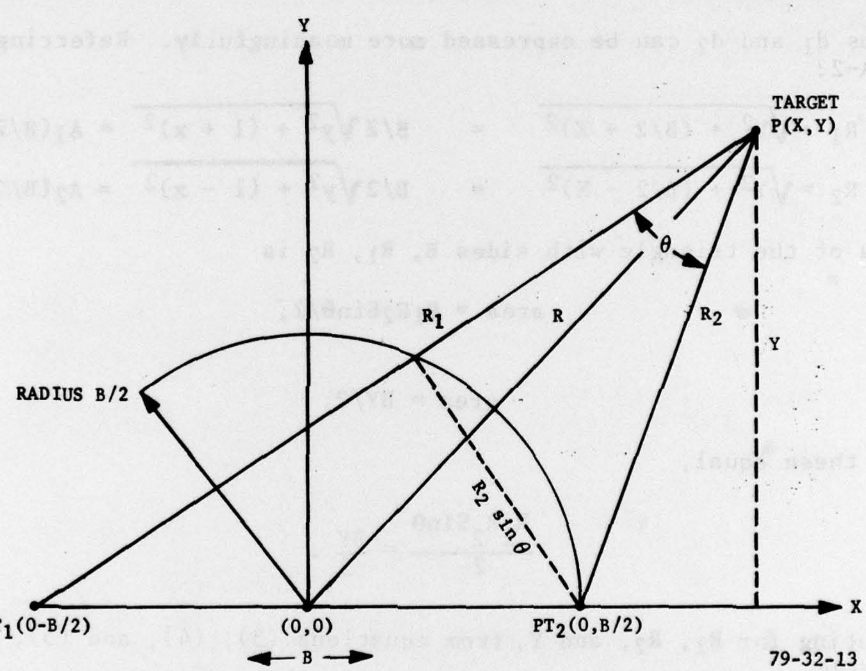

FIGURE A-2. TARGET LOCATION GEOMETRY

and

$$\frac{A_1A_2}{2y} = \frac{1}{\sin\theta} . \quad (11)$$

But from equations (1), (4), and (5), $A_1A_2/\ 2y = d_1$,

hence,
$$d_1 = \frac{1}{\sin\theta} \quad (12)$$

and
$$E_1 = Bed_1 = \frac{Be}{\sin\theta} \quad (13)$$

Similarly expressing d_2,

$$d_2 = d_1\sqrt{x^2 + y^2} = d_1\sqrt{\frac{X^2 + Y^2}{(B/2)^2}} \quad (14)$$

but

$$R = \sqrt{X^2 + Y^2} \quad (15)$$

then

$$d_2 = d_1 \left(\frac{R}{B/2}\right) = \frac{1}{\sin\theta} \times \frac{R}{B/2} = \frac{2R}{B\sin\theta} \quad (16)$$

for which

$$E_2 = Bed_2 = \frac{2Re}{\sin\theta} . \quad (17)$$

While less convenient for computations, pertinent qualifications inherent to phototheodolite tracking errors stem from equations (13) and (17).

1. E_1 is in the nature of a lateral error; E_2 a longitudinal error.

2. Error is inversely proportional to $\sin\theta$. Maximizing $\sin\theta$ minimizes error. At the intersection of the baseline bisector and baseline-diameter circle, $\sin\theta$ equals unity. Angle θ is a function of target location with respect to the baseline.

3. For points within the baseline-diameter circle, E_1 will be greater than E_2; lateral error will be greater than longitudinal error.

4. For points outside the baseline-diameter circle, E_2 will be greater than E_1; longitudinal error will be greater than lateral error.

For simplicity, the development of E has assumed the target to be in a horizontal plane through the phototheodolites. What has been said for the horizontal plane applies for targets in an inclined plane. Except for close-in tracking at high altitudes, however, the value of E will not materially change from that obtained in the horizontal plane.

From the discussion given on system errors, it should be recognized that there is no single answer to the question of how accurate the phototheodolite system is. The question must be qualified by various considerations, most important of which is that of specifying target tracking area.

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